# Computational Neuroscience: Neuronal Dynamics of Cognition

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

## Decision models:

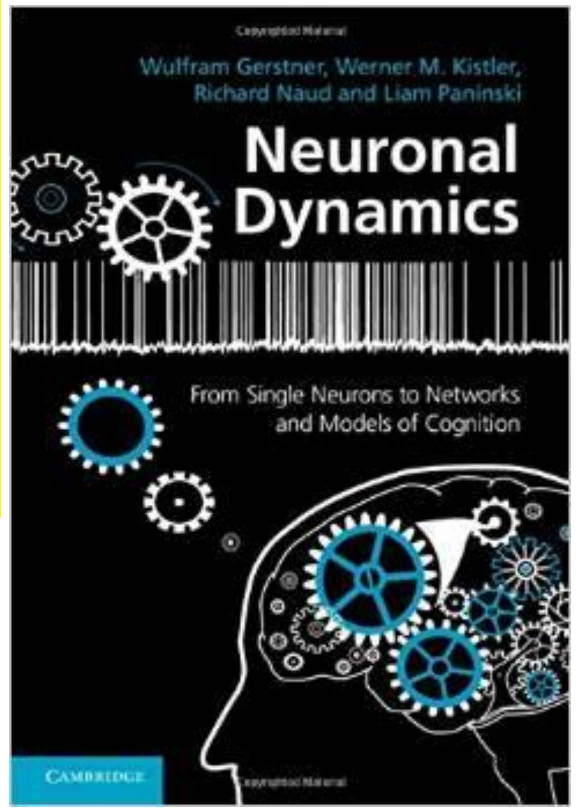
## Competitive dynamics

Wulfram Gerstner

EPFL, Lausanne, Switzerland

*Reading for week 9*:
NEURONAL DYNAMICS
Ch. 16 (except 16.4.2)

Cambridge Univ. Press




1. **Introduction**
   - decision making
2. **Perceptual decision making**
   - V5/MT
   - Decision dynamics: Area LIP
3. **Theory of decision dynamics**
   - competition via shared inhibition
   - effective 2-dim model
4. **Solutions**
   - symmetric case
   - biased case
5. **Simulations and Experiments**
   - simulations and theory
   - simulations and experiments
6. **Decisions, actions, volition**
   - the problem of free will

# 1. How do I decide?

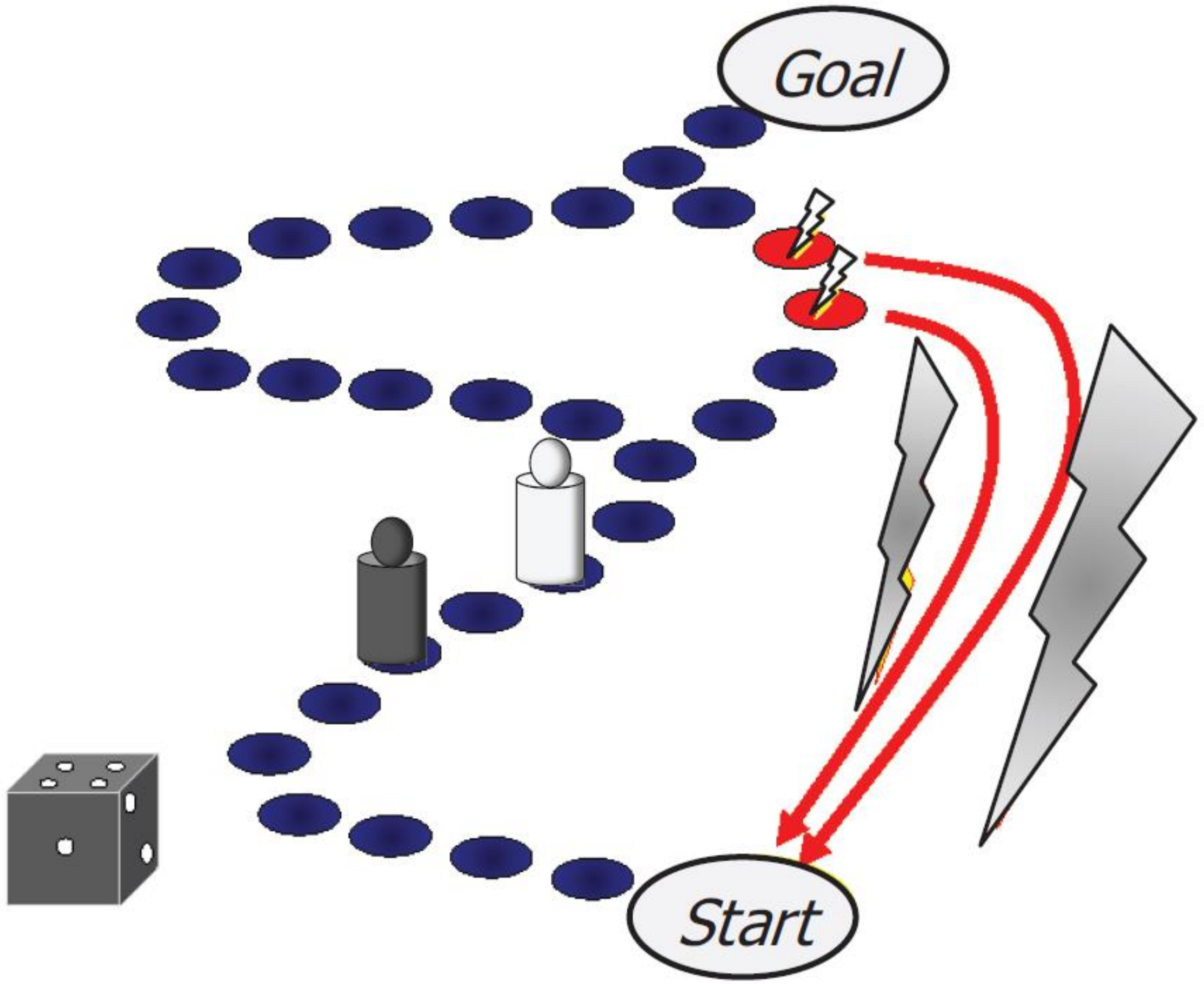
**We take decisions all the time**

- Coffee before class or not?

- Vote for candidate A or B?


- Turn left or right at the crossing?

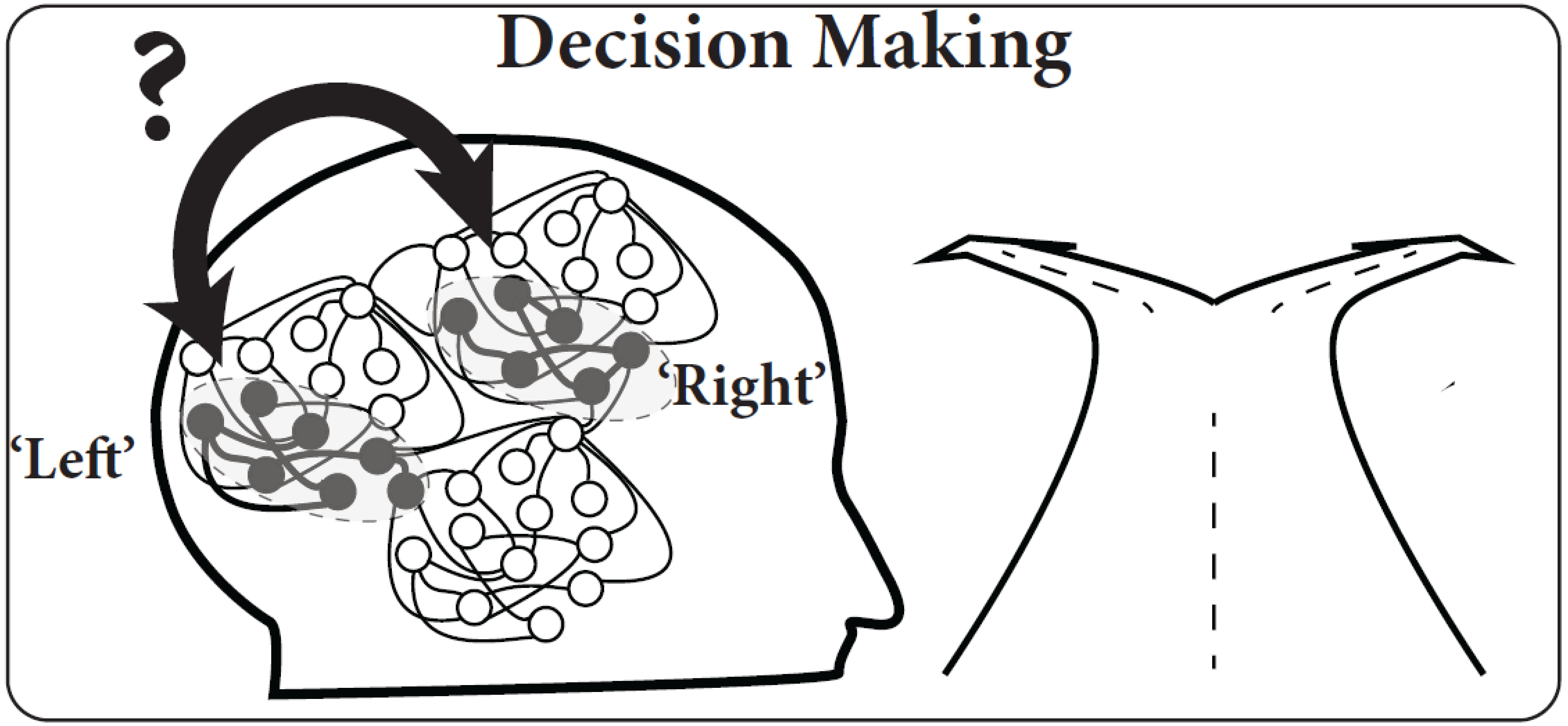
# 1. How do I decide?



# 1. Decision making

*turn*

*Left?* *Right?*



# 1. Review: High-noise activity equation

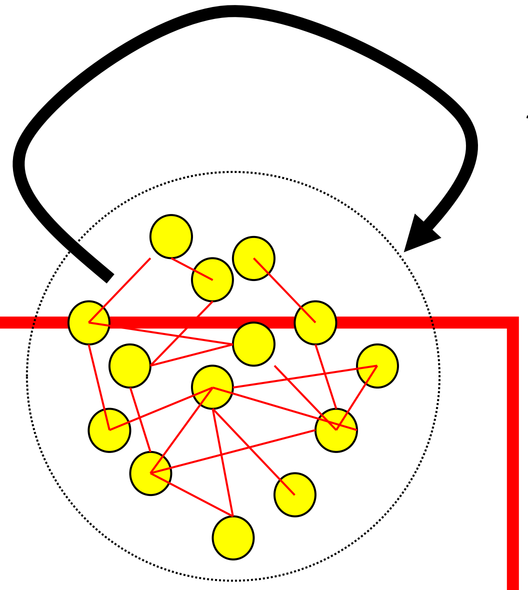
Population activity

$$A(t) = F(h(t))$$

Membrane potential caused by input

$$\tau \frac{d}{dt} h(t) = -h(t) + R\ I(t)$$

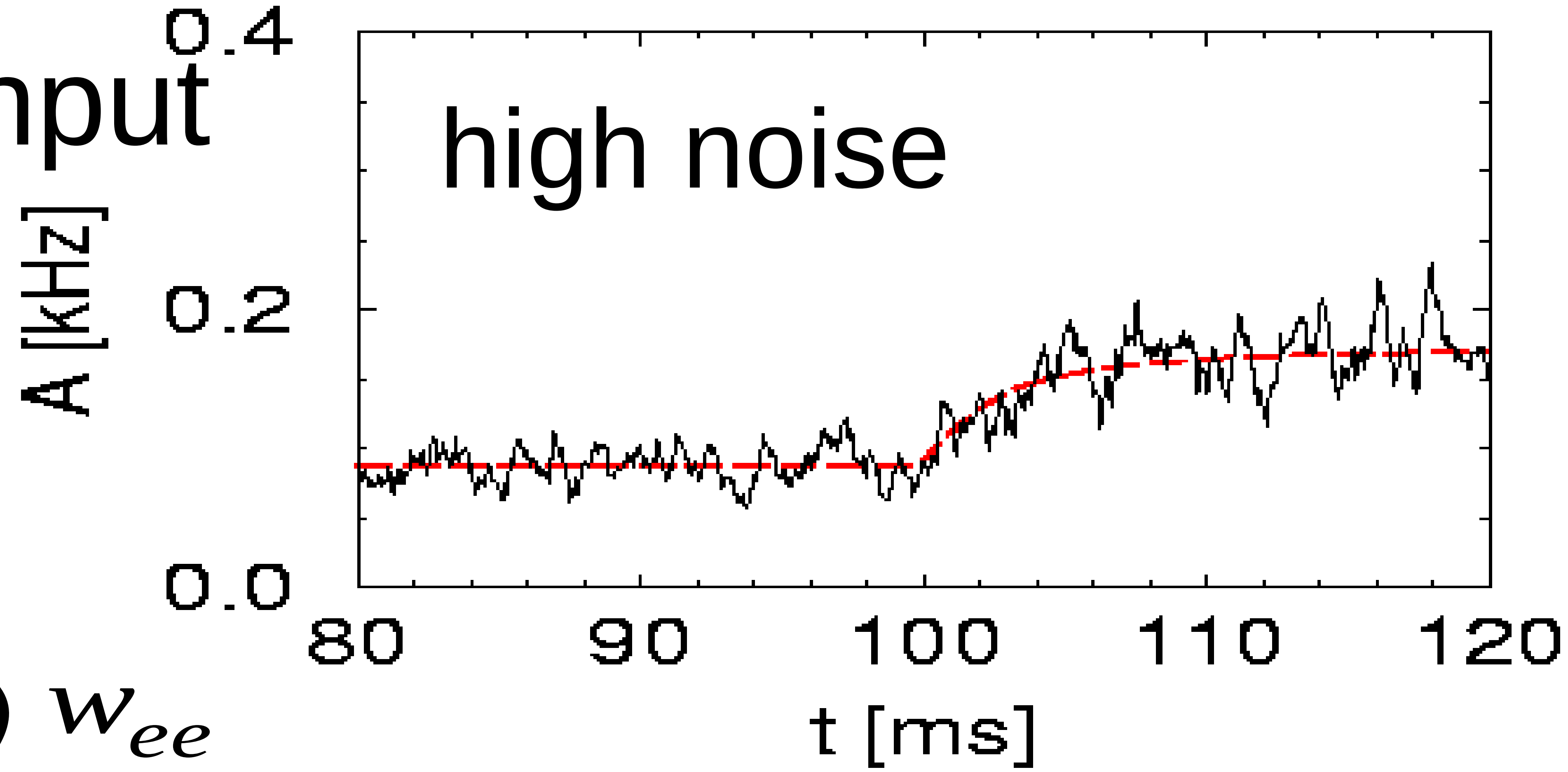
$$\tau \frac{d}{dt} h(t) = -h(t) + R I^{ext}(t) + w_{ee} F(h(t))$$

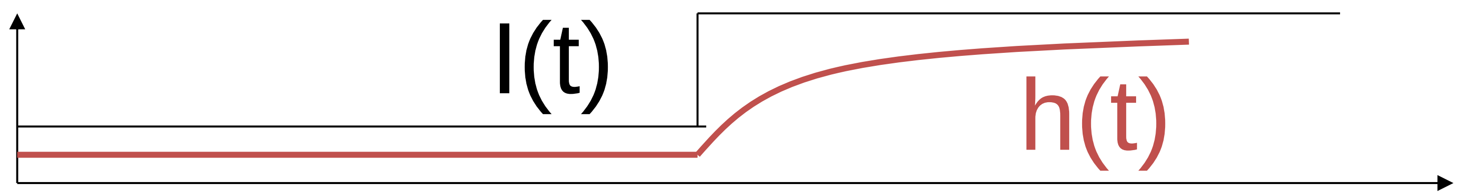


$w_{ee}$

noise model A

(escape noise/fast noise)



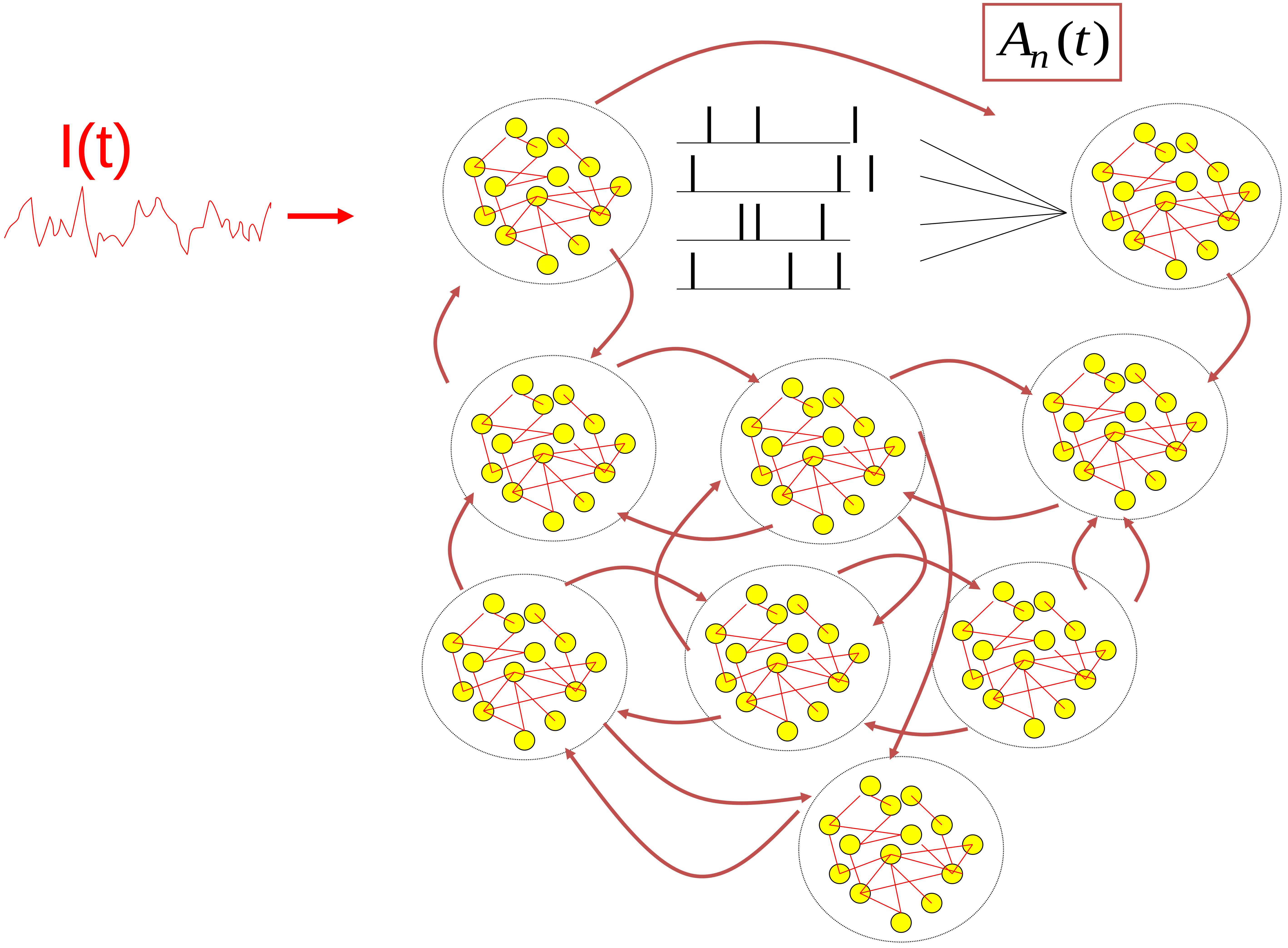

slow transient

$$A(t) = F(h(t))$$

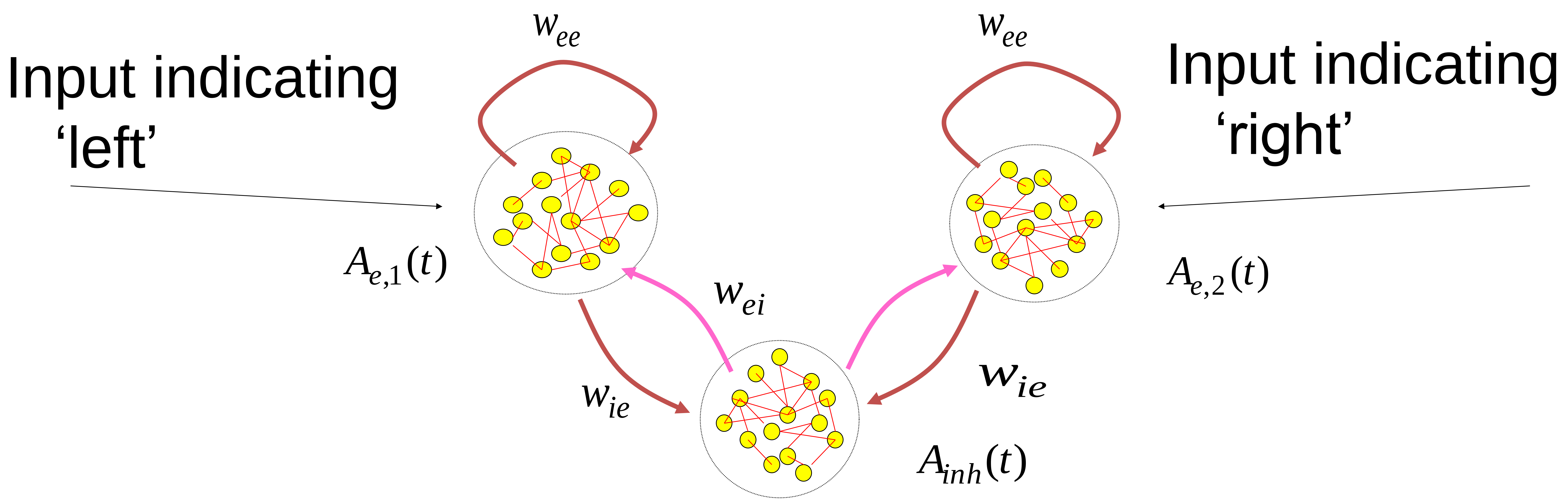
Attention:

- valid for high noise only, else transients might be wrong
- valid for high noise only, else spontaneous oscillations may arise

# 1. Review: microscopic vs. macroscopic



# 1. Competition between two populations



# 1. How do YOU decide? Make a commitment and indicate choice

Suppose you got a winning ticket,
pick your money at closest post office

30CHF tomorrow / 100 CHF May first next year

90CHF tomorrow / 100 CHF May first next year

‘Neuro-economics’

# 1. Perceptual decision making?

## Bisection task:

‘Is the middle bar shifted to the left or to the right?’

# 1. decision making - aims

Decisions are everywhere

Model: populations of neurons

Competition

Perceptual Decision task

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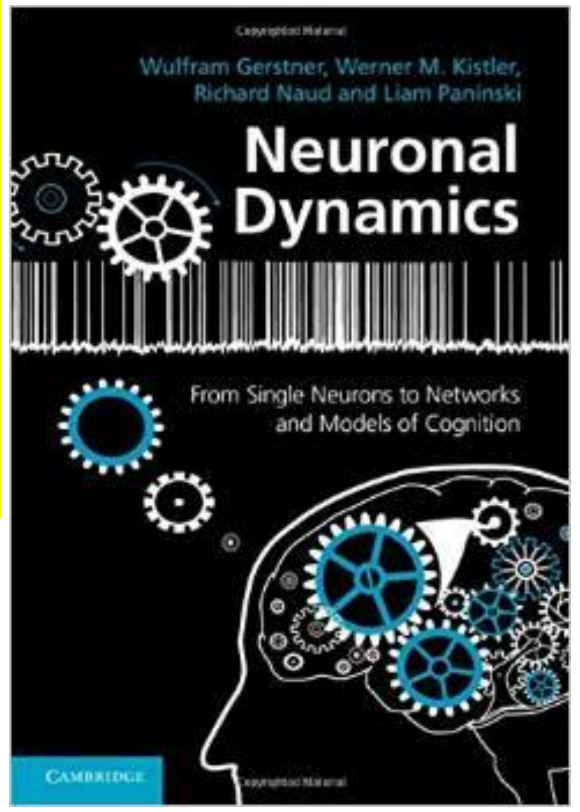


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# 2. Perceptual decision making?

## Bisection task:

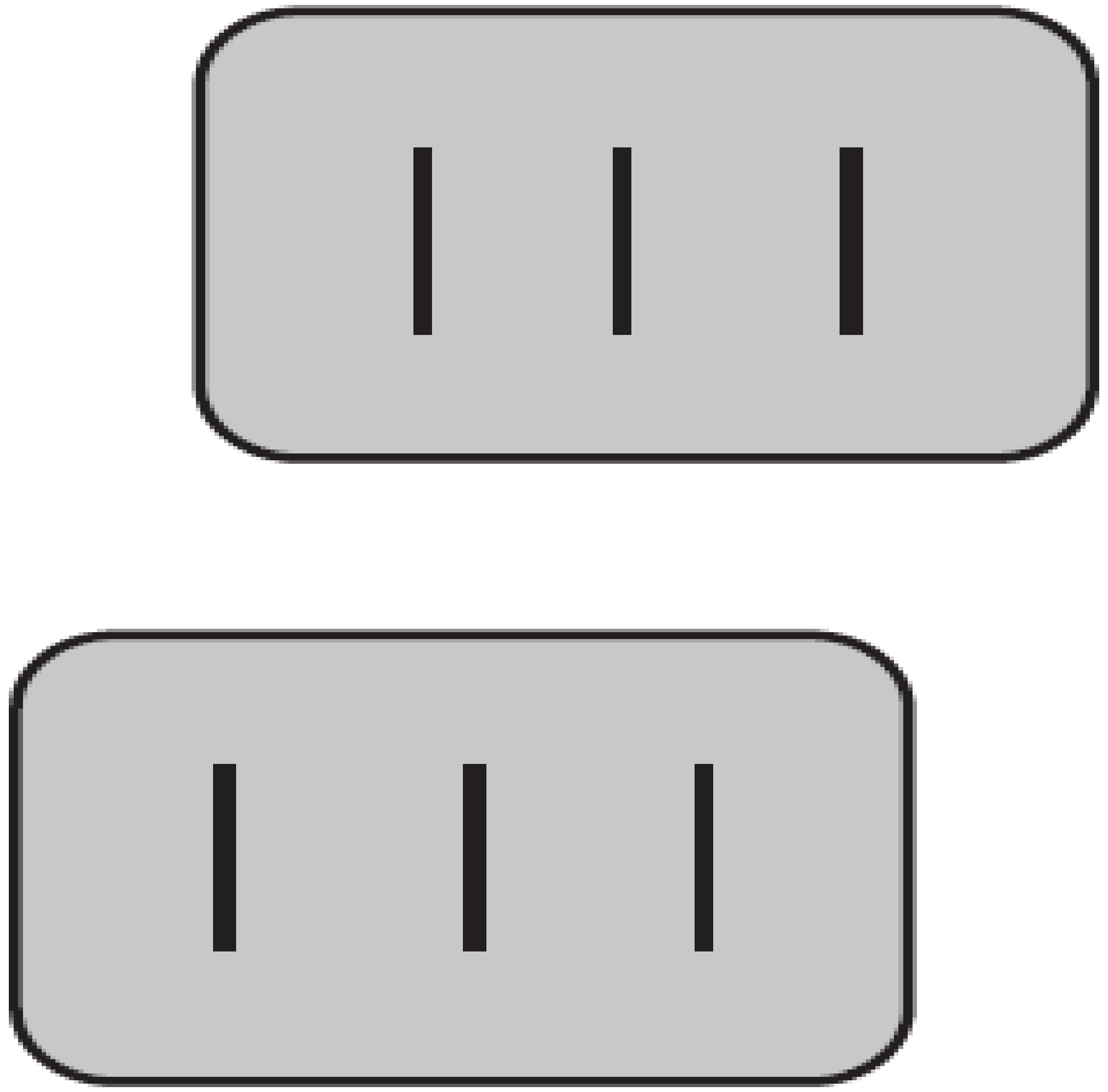
‘Is the middle bar shifted to the left or to the right?’

e.g., Herzog lab, EPFL

# 2. Perceptual decision making?

## Bisection task:

'Is the middle bar shifted to the left or to the right?'



e.g., Herzog lab, EPFL

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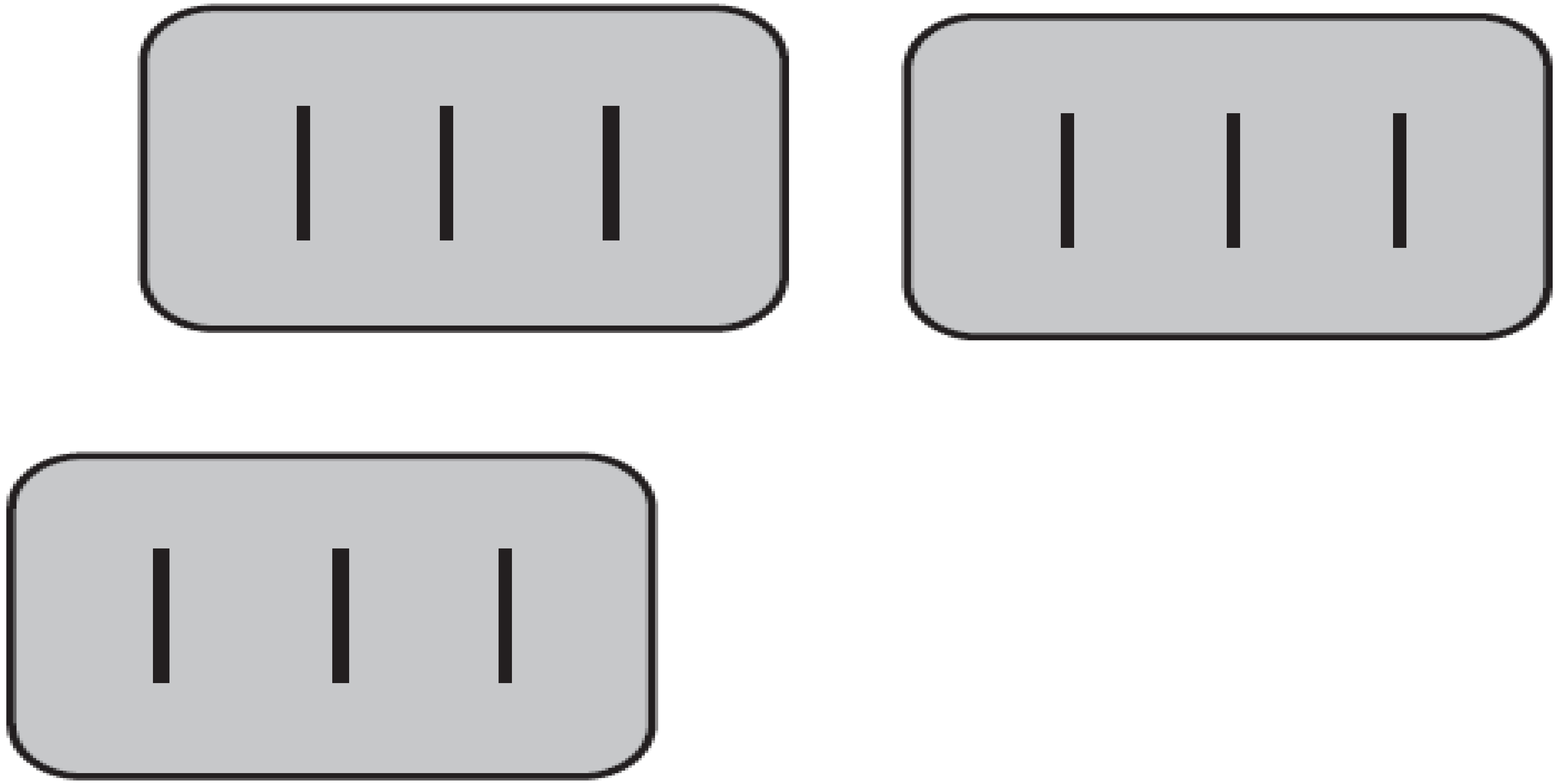
‘Is the middle bar shifted to the left or to the right?’



e.g., Herzog lab, EPFL

# 2. Perceptual decision making?

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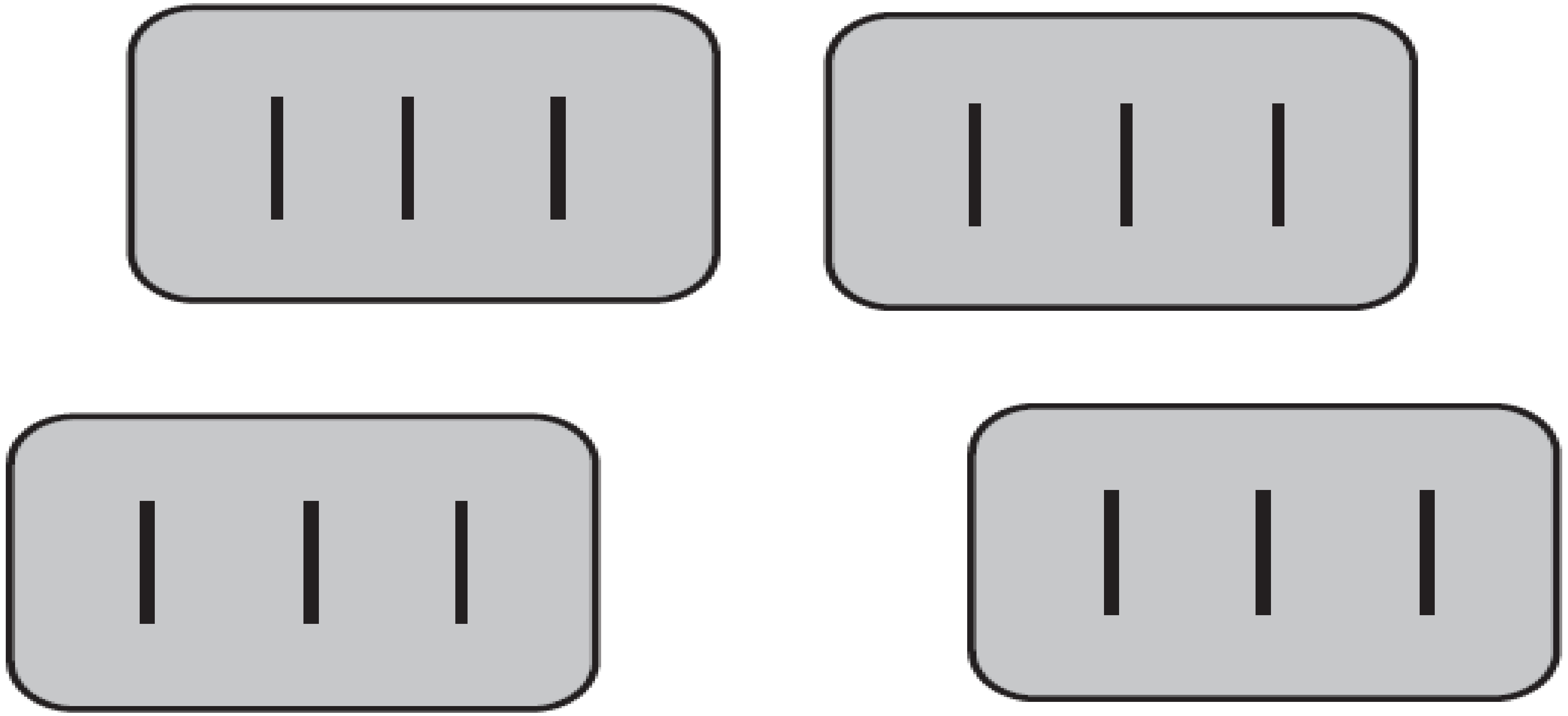
‘Is the middle bar shifted to the left or to the right?’



e.g., Herzog lab, EPFL

# 2. Detour: receptive fields in V5/MT

visual cortex

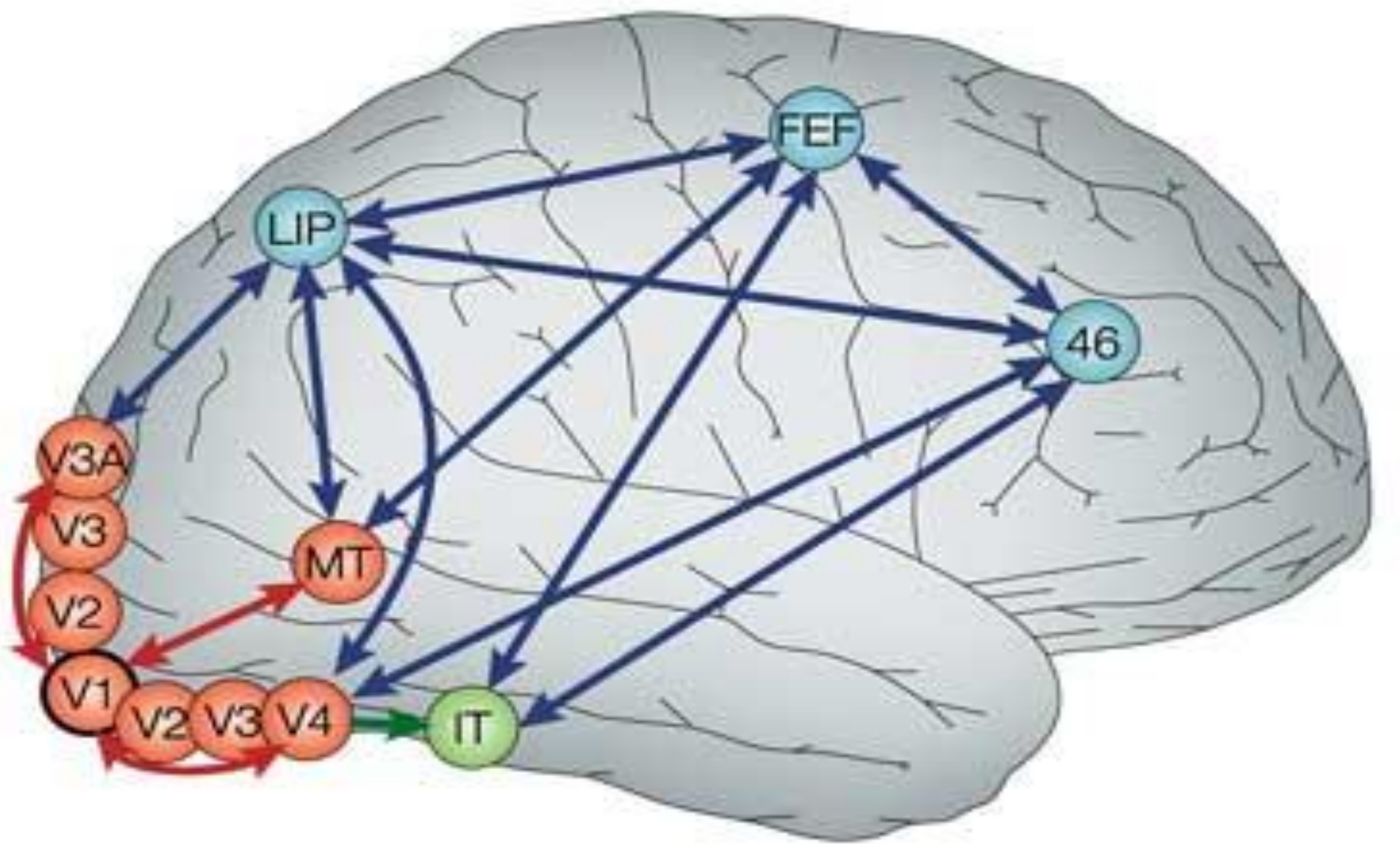
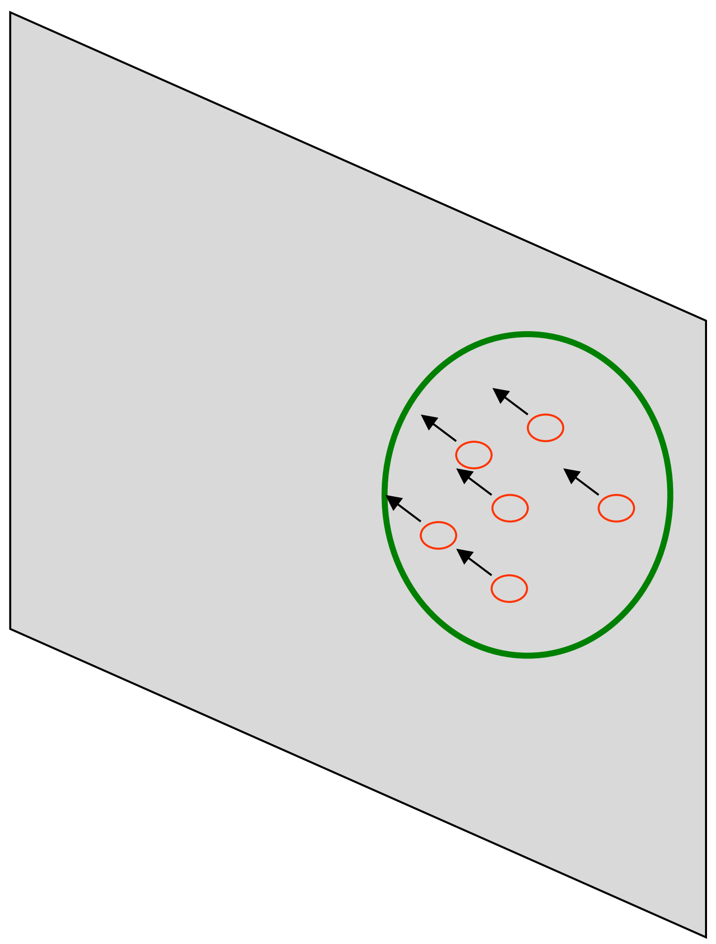



*IMAGE* Nature Reviews | Neuroscience



1) Cells in visual cortex MT/V5 respond to motion stimuli

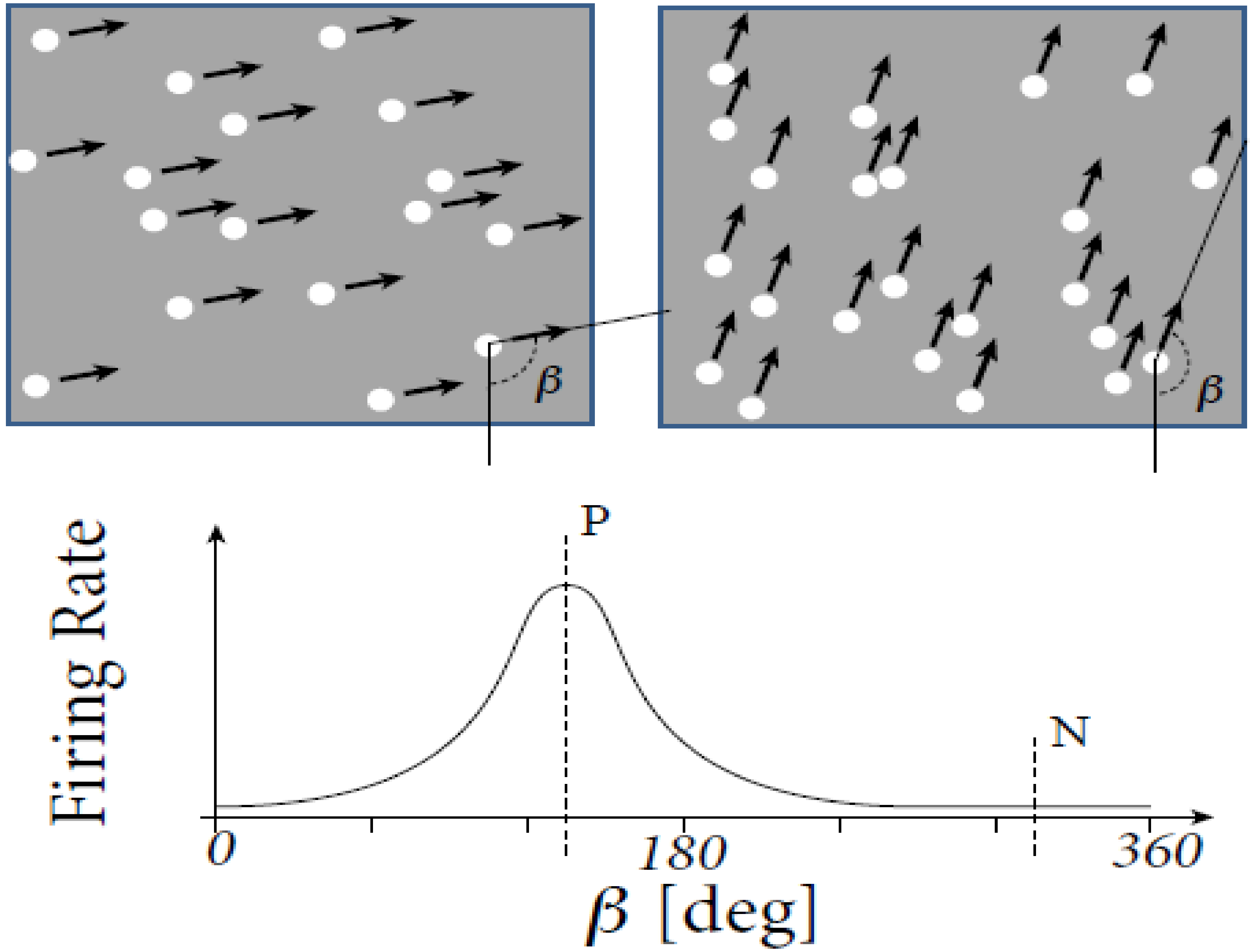
2) Neighboring cells in visual cortex MT/V5 respond to motion in similar direction

cortical columns

*Albright, Desimone,Gross, J. Neurophysiol, 1985*

# 2. Detour: receptive fields in V5/MT

Recordings from a single neuron in V5/MT

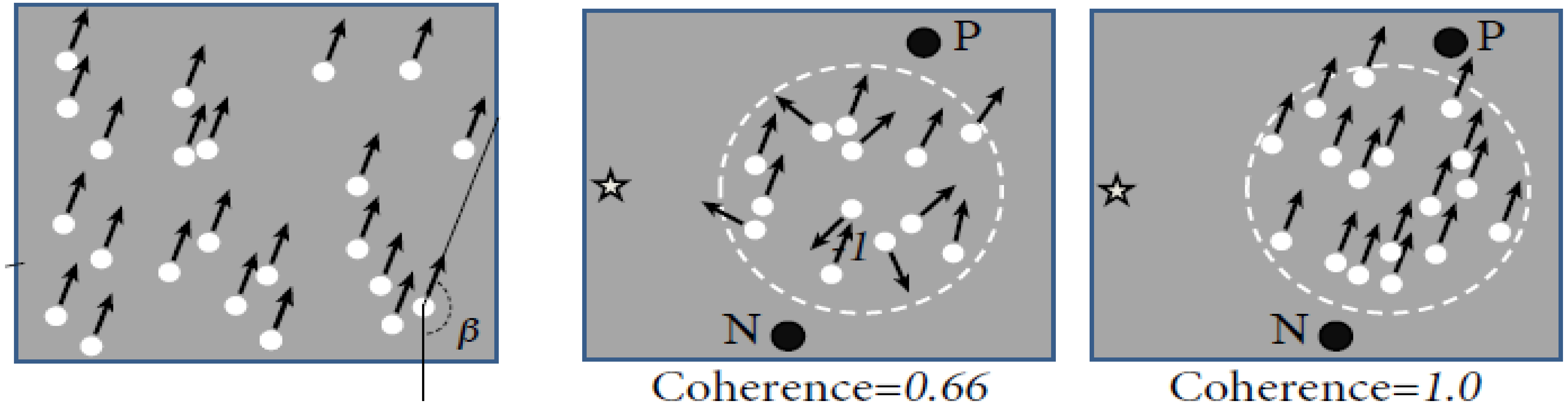



Receptive Fields depend on direction of motion

*Random moving dot stimuli:*

*e.g.Salzman, Britten, Newsome, 1990*
*Roitman and Shadlen, 2002*
*Gold and Shadlen 2007*

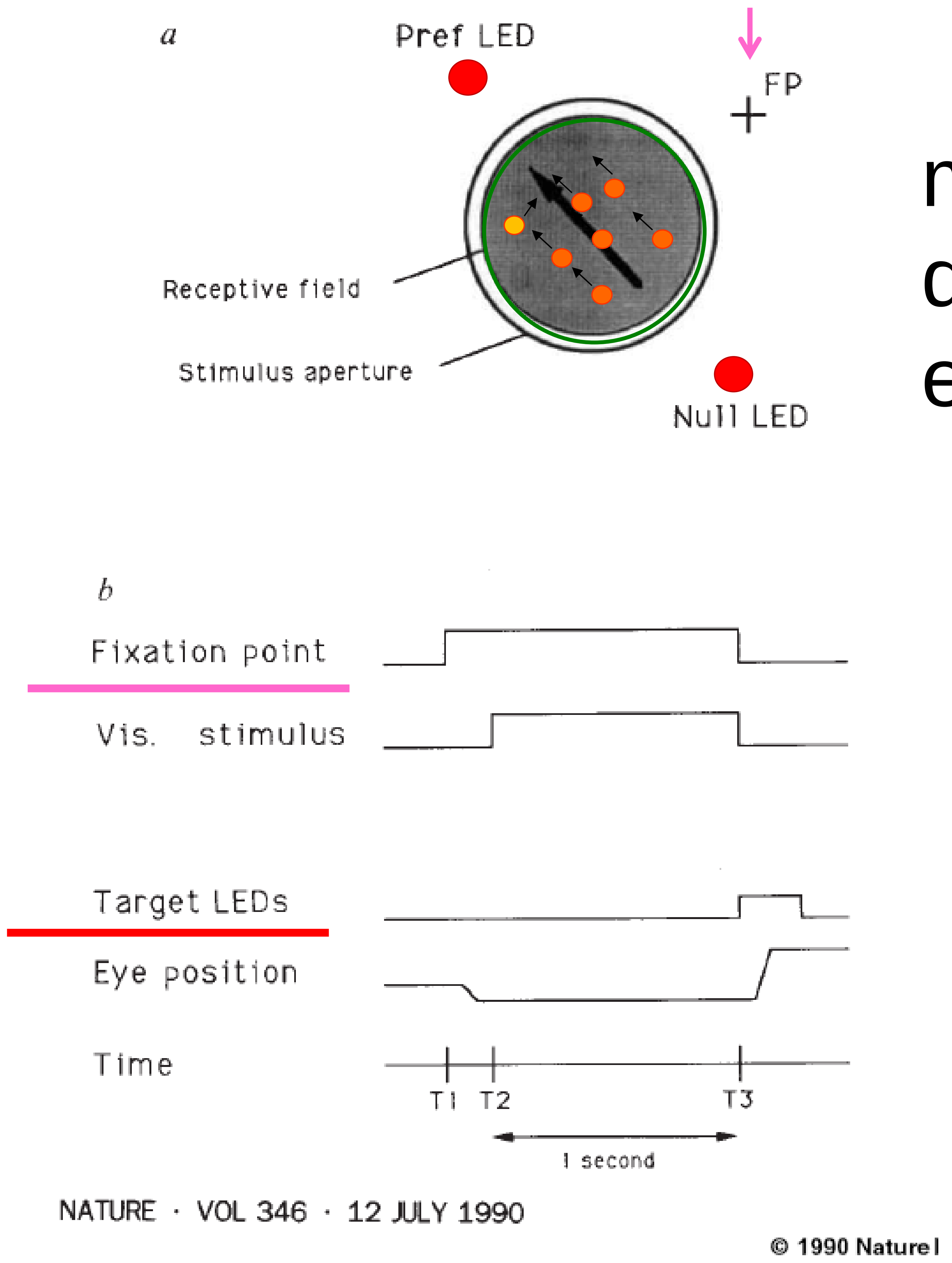
# 2. Detour: receptive fields in V5/MT




Receptive Fields depend
on direction of motion: β = preferred direction = P

*Image:*
*Gerstner et al. (2014),*
*Neuronal Dynamics*

# 2. Experiment of Salzman et al. 1990

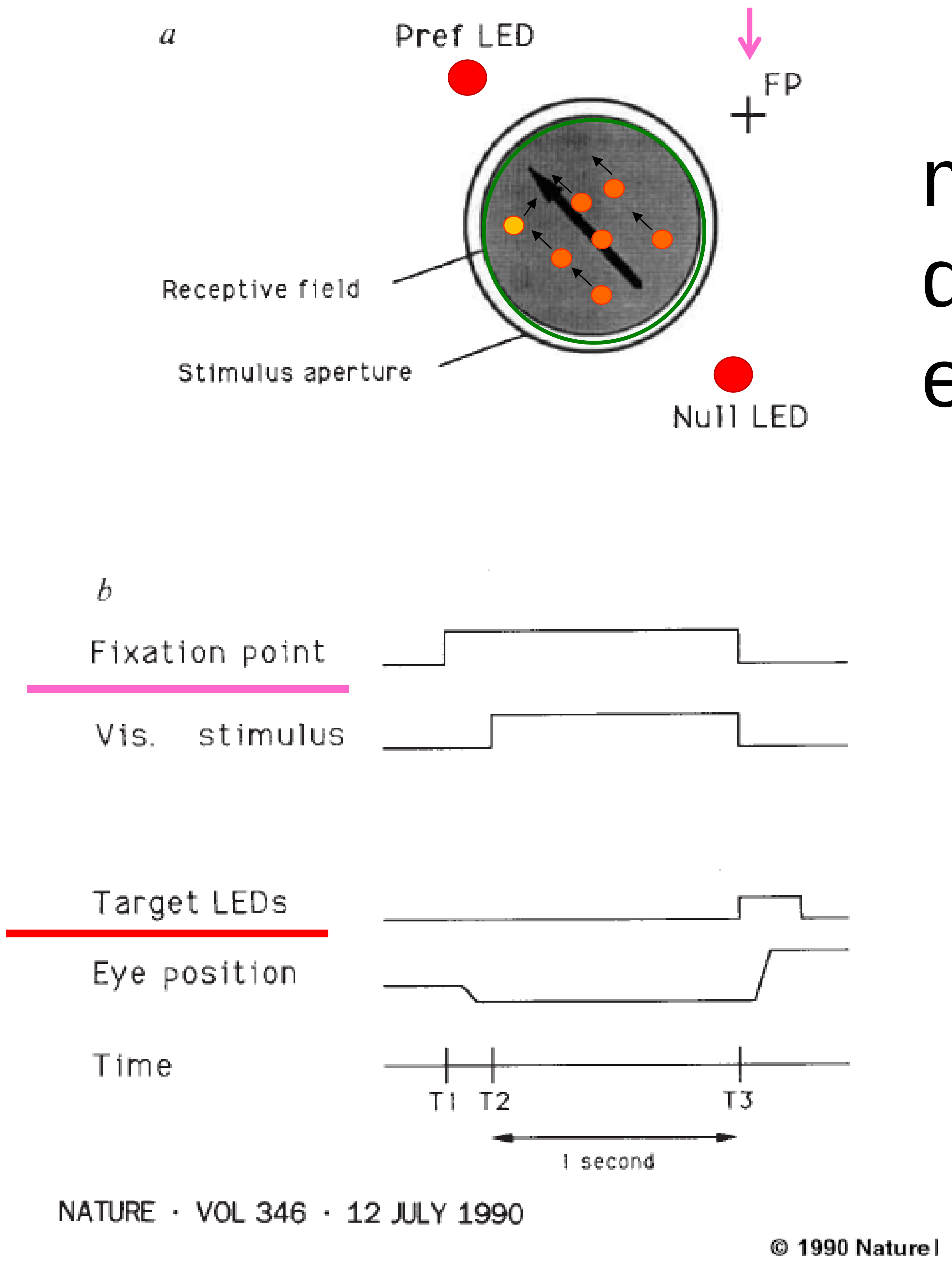



monkey indicates
decision by
eye movement

Eye movement

*Image: Salzman, Britten, Newsome, 1990*

# 2. Experiment of Salzman et al. 1990

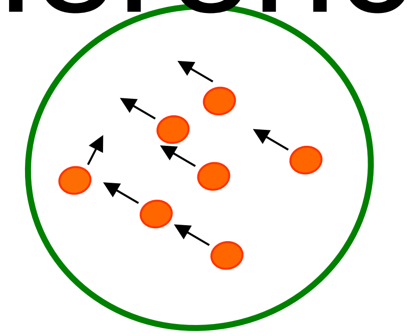



monkey indicates decision by eye movement

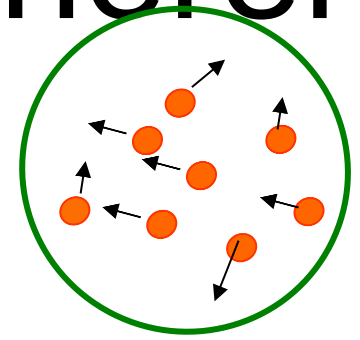
Eye movement

*Image: Salzman, Britten, Newsome, 1990*

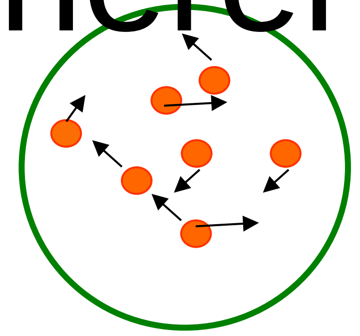
coherence 0.8=80%



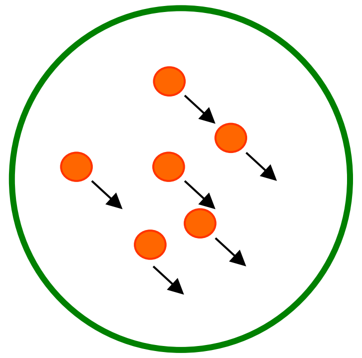
coherence 0.5 = 50%



coherence 0.0



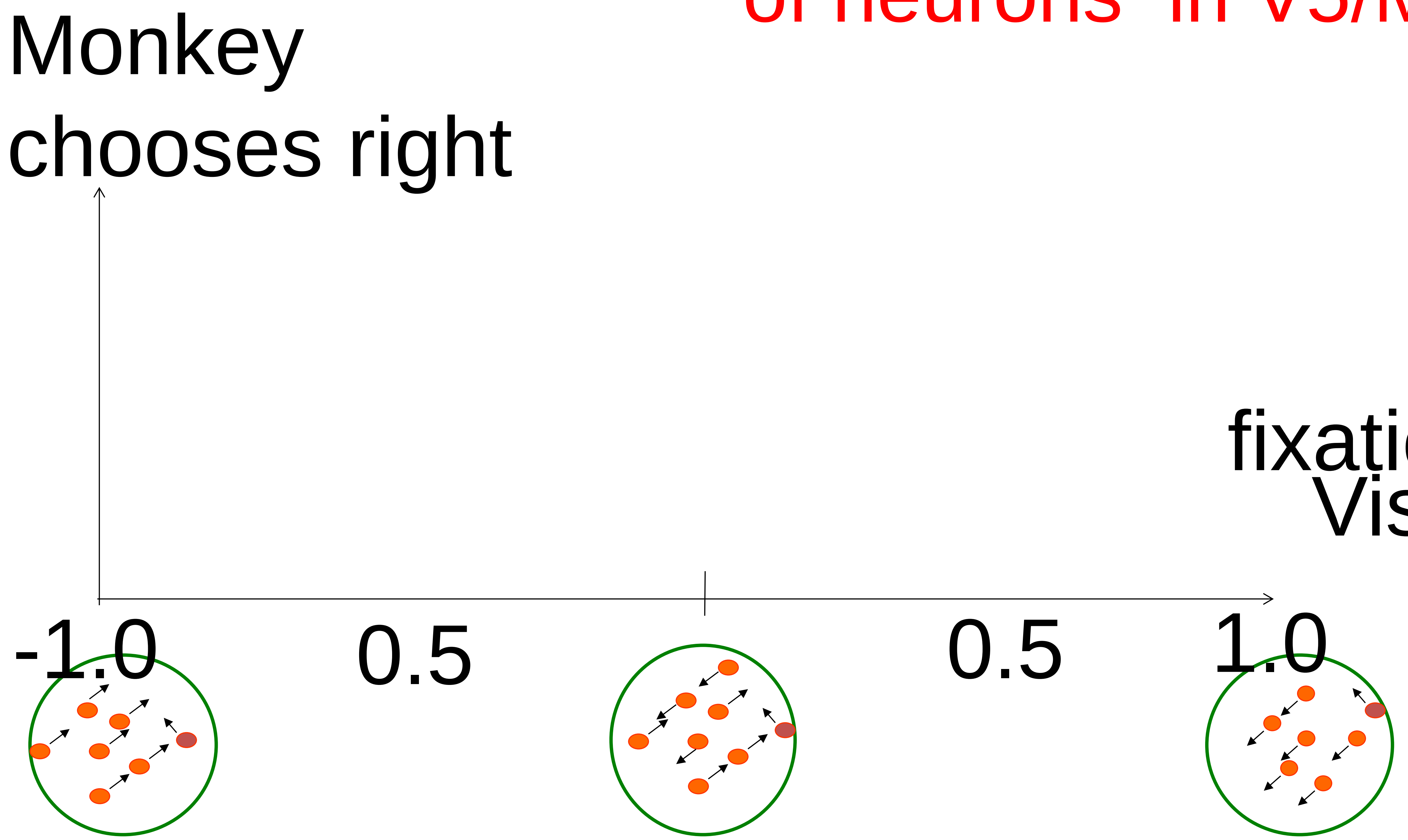
coherence -1.0

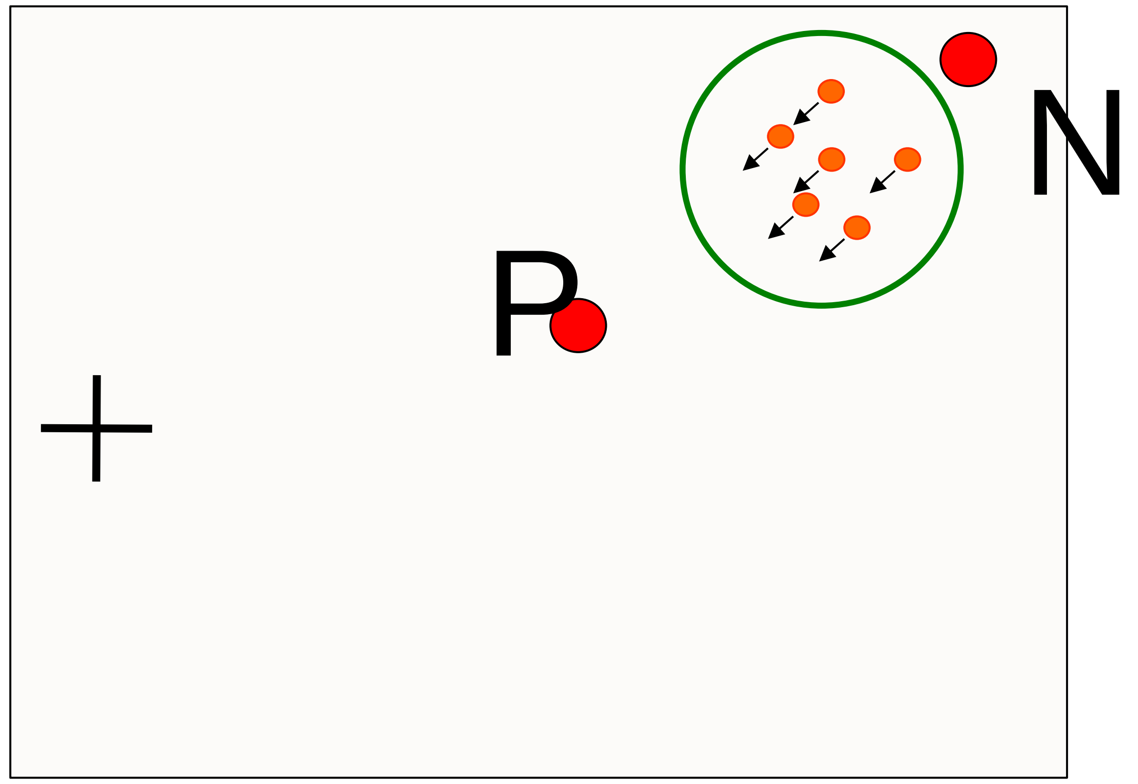


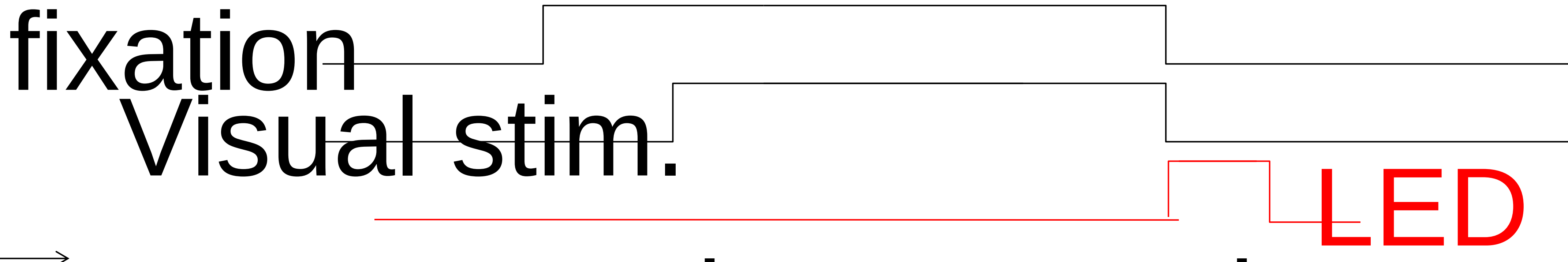
opposite direction

# 2. Experiment of Salzman et al. 1990

Monkey behavior w. or w/o Stimulation of neurons in V5/MT



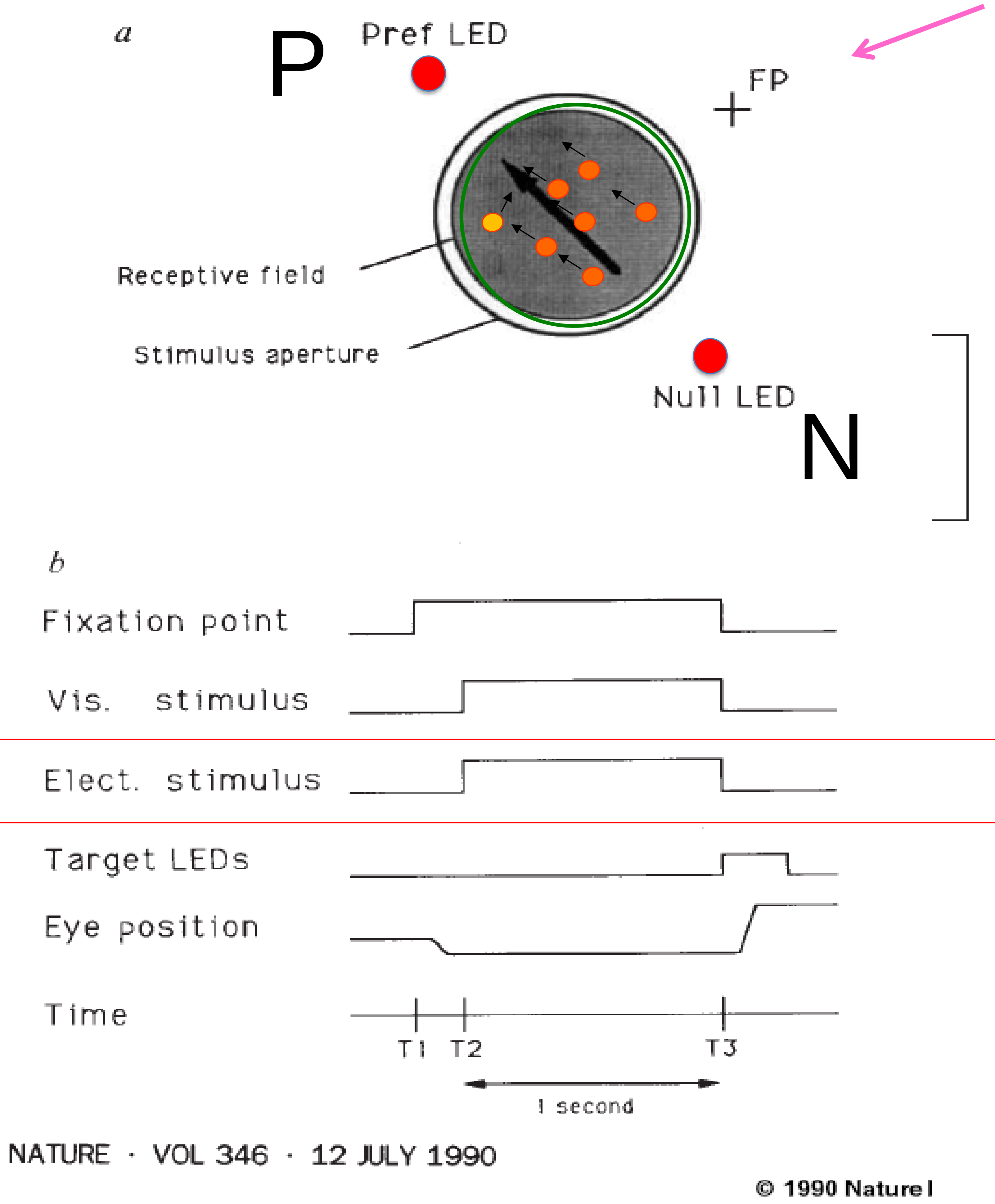




X = coherent motion to bottom right

No bias, each point moves in random direction

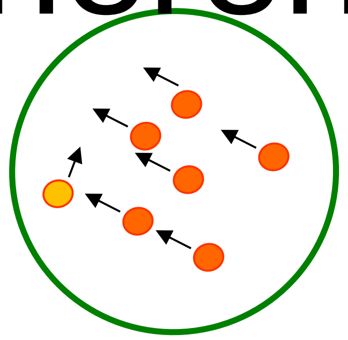
*Salzman, Britten, Newsome, 1990*

# 2. Experiment of Salzman et al. 1990

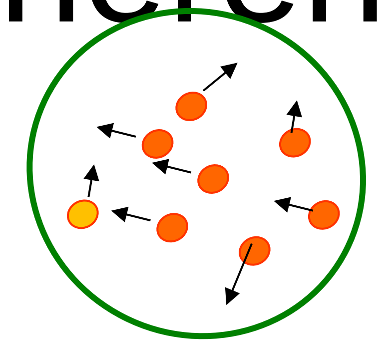



excites this group of neurons

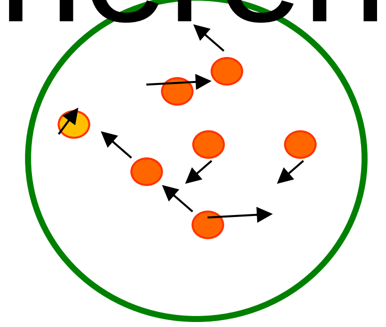
coherence 0.8=80%



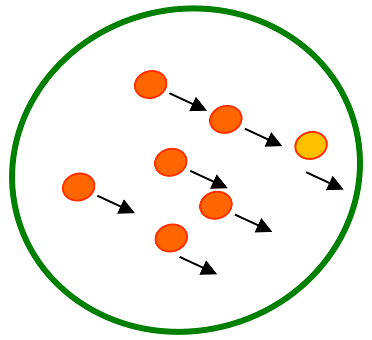
coherence 0.5 = 50%



coherence 0.0



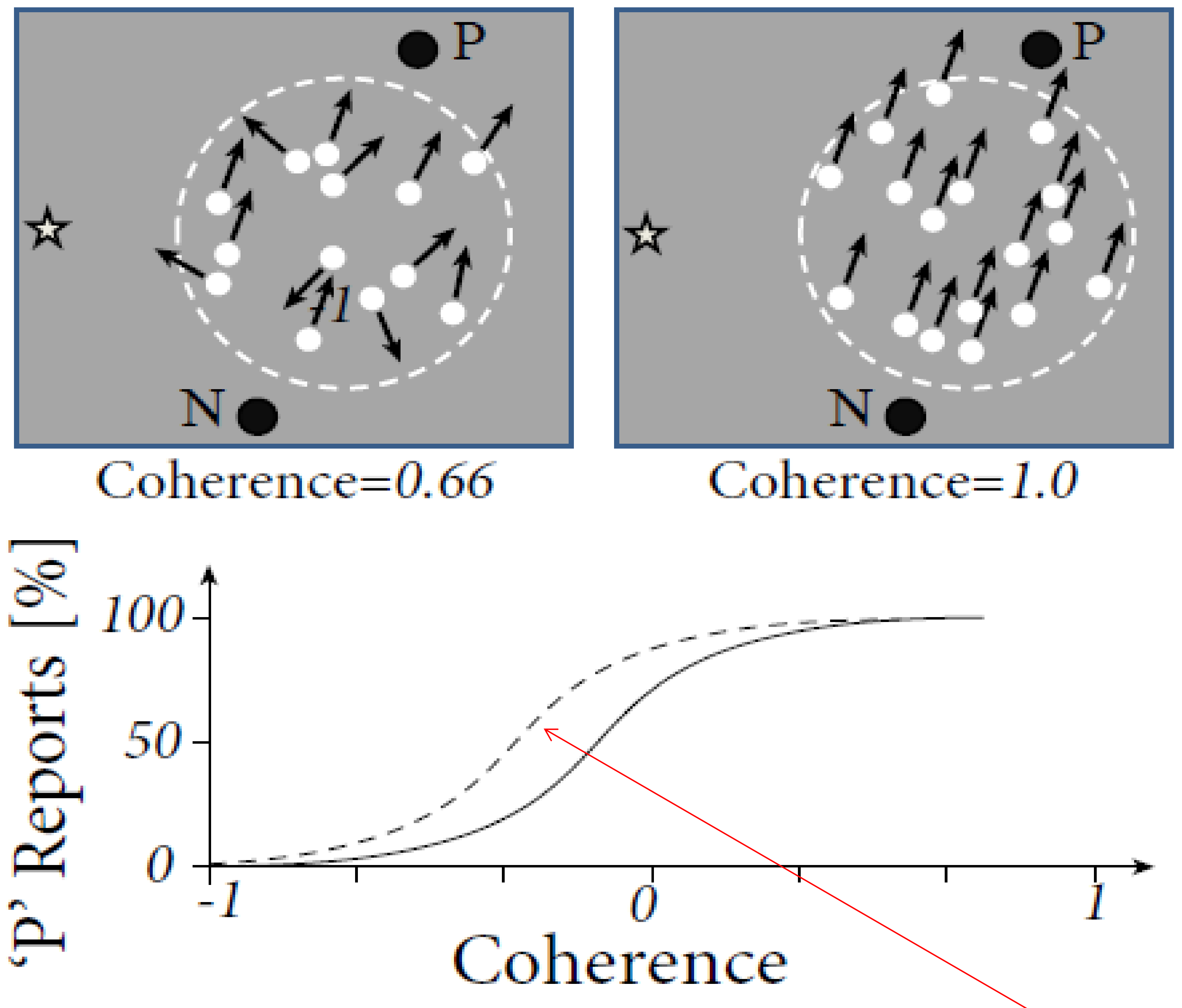
coherence -1.0



# 2. Experiment of Salzman et al. 1990

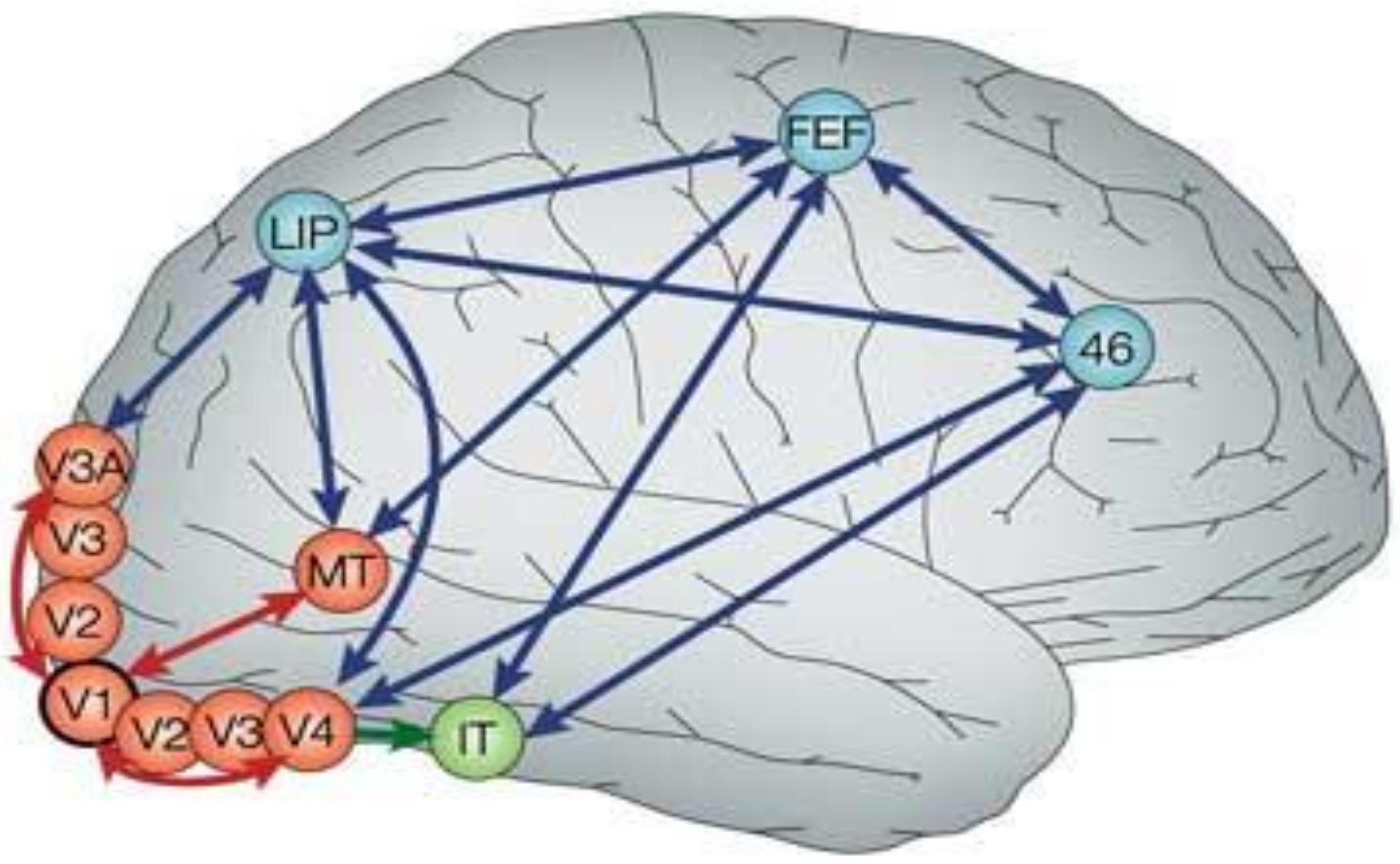
## Behavior: psychophysics

*Image:*
*Gerstner et al. (2014), Neuronal Dynamics; Redrawn after Salzman et al, 1990*




With stimulation

# 2. Perceptual Decision Making




Nature Reviews | Neuroscience

## 9.1 Review: Population dynamics

- competition

## 9.2 Perceptual decision making

- V5/MT
- Decision dynamics: Area LIP

## 9.3 Theory of decision dynamics

- shared inhibition
- effective 2-dim model

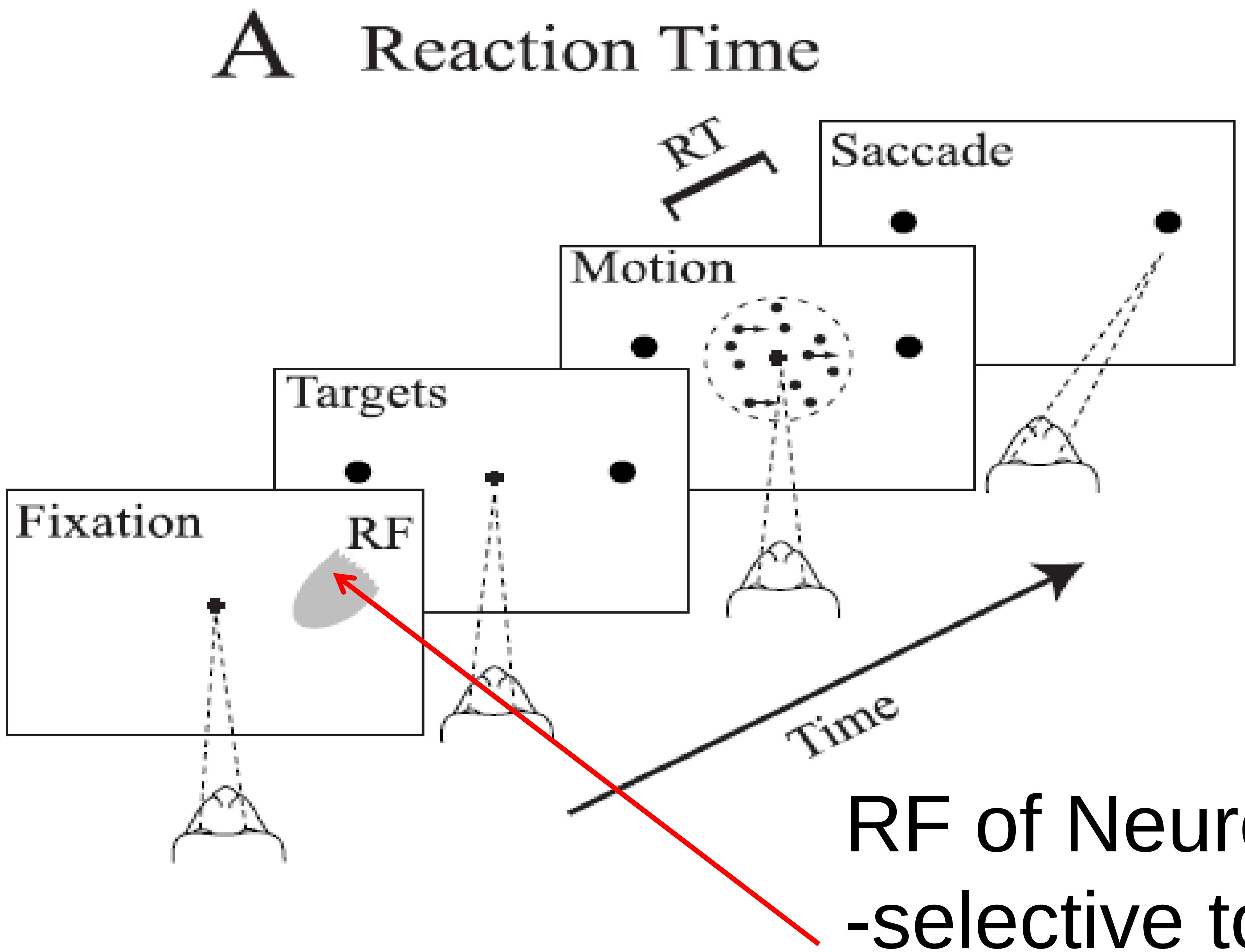
## 9.4. Decisions in connected pops.

- unbiased case
- biased input

## 9.5. Decisions, actions, volition

- the problem of free will

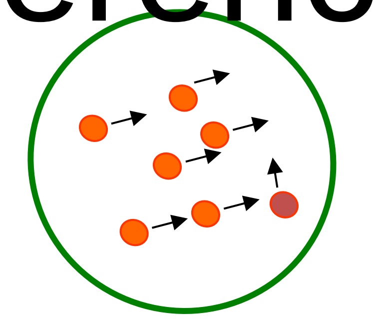
# 2. Experiment of Roitman and Shadlen in LIP (2002)



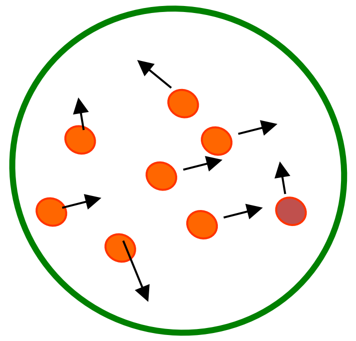

RF of Neuron in LIP:
-selective to target of saccade
- response increases faster if signal is stronger
- activity is noisy

LIP is somewhere between MT (movement detection) and Frontal Eye Field (saccade control)

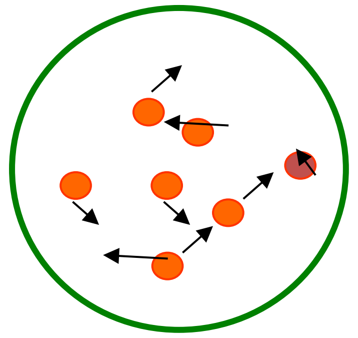
coherence 85%



coherence 50%



coherence 0%



*Roitman and Shadlen 2002*

# 2. Experiment of Roitman and Shadlen in LIP (2002)

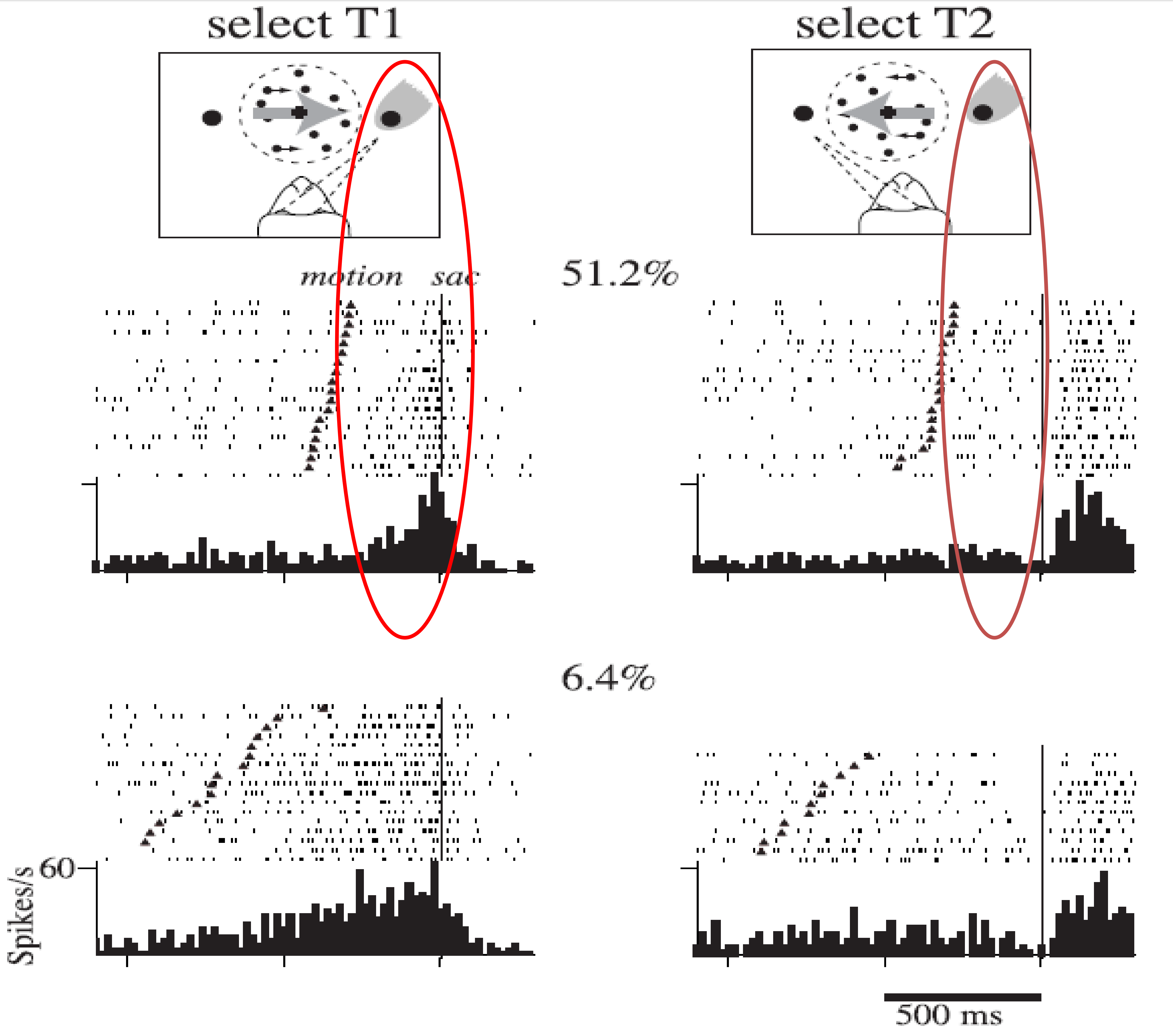



*Figure 4.* Response of an LIP neuron during the RT-direction-

Neurons in LIP:
- selective to target of saccade
- increases faster if signal is stronger
- activity is noisy

LIP is somewhere between MT (movement detection) and Frontal Eye Field (saccade control)

# 2. Experiment of Roitman and Shadlen in LIP (2002)

**Neurons in LIP**:

- Selective to target of saccade
- Activity increases faster if signal is stronger
- Activity is noisy
- Located in the signal processing stream between sensory areas and saccade control
- I do not claim that these neurons ‘take the decision’
- Interesting correlations with decision outcome

Quiz

Receptive field in LIP

[ ]  related to the target of a saccade

[ ]  depends on movement of random dots

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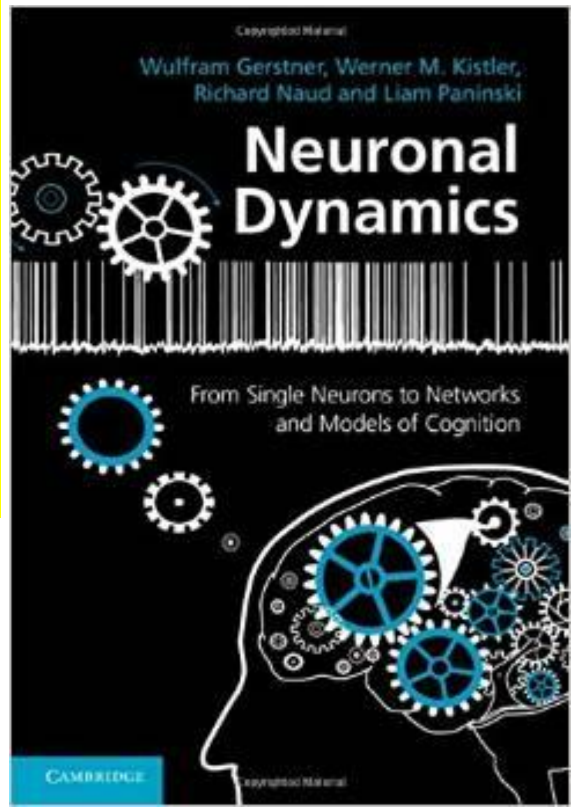


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# 3. Theory of decision dynamics

$$A_n(t) = F(h_n(t))$$

activity equations

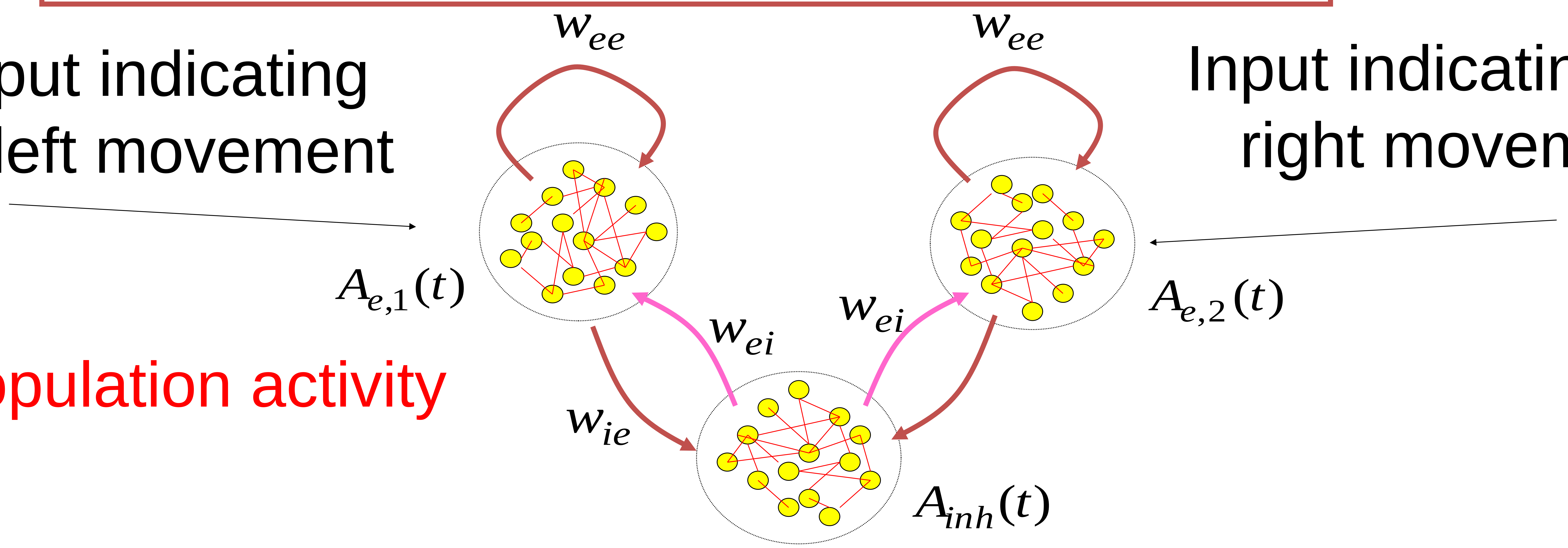
Membrane potential caused by input

$$\tau \frac{d}{dt} h_1(t) = -h_1(t) + R\, I_1^{ext}(t) + w_{ee}\, F(h_1(t)) + w_{ei}\, F(h_{inh}(t))$$

$$\tau \frac{d}{dt} h_2(t) = -h_2(t) + R\, I_2^{ext}(t) + w_{ee}\, F(h_2(t)) + w_{ei}\, F(h_{inh}(t))$$

Input indicating left movement

Input indicating right movement



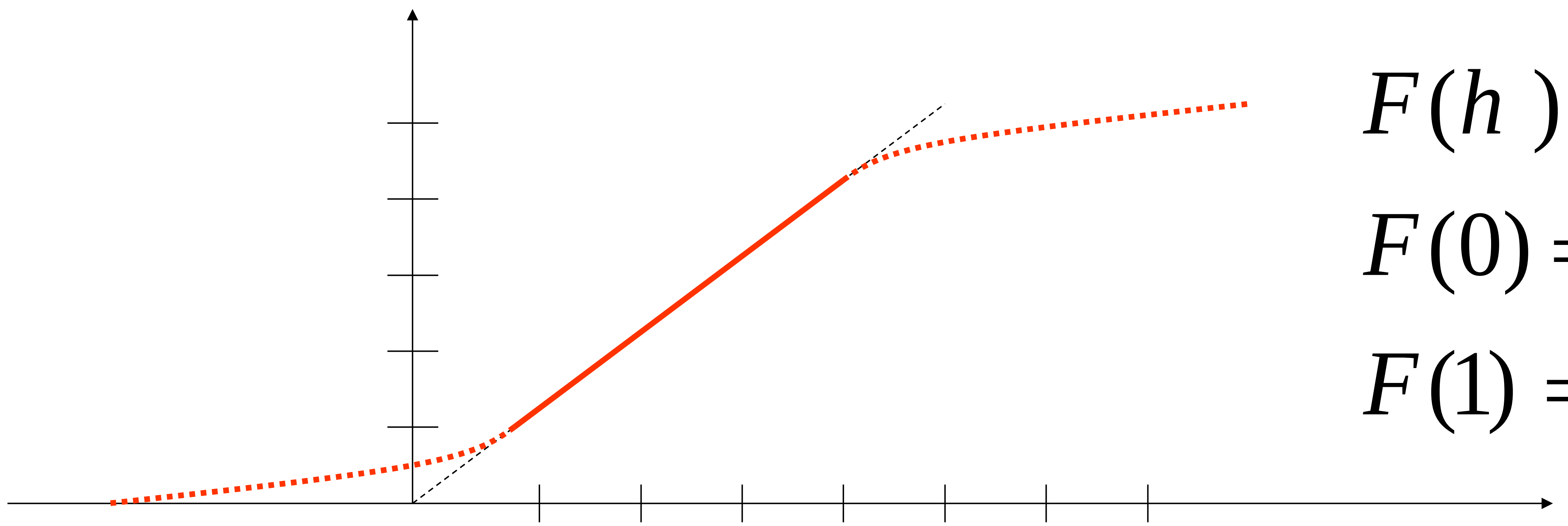

population activity

# 3. Inhibitory population: linear f-I curve

Population activity

$$A_n(t) = F(h_n(t))$$

activity equations



$$F(h) = h \quad for \;\; 0.2 < h < 0.8$$

$$F(0) = 0.1$$

$$F(1) = 0.9$$

Inhibitory Population

$$A_{inh}(t) = F(h_{inh}(t)) = h_{inh}(t)$$

Assumption 1: linear

Assumption 2: fast

# 3. Reduction to 2 dimensions

Inhibitory population: fast

Membrane potential caused by input (excitatory population)

$$\tau \frac{d}{dt} h_1(t) = -h_1(t) + R I_1^{ext}(t) + w_{ee} F(h_1(t)) + w_{ei} F(h_{inh}(t))$$

# 3. Effective 2-dim. model

$$A_n(t) = F(h_n(t))$$

activity equations

Membrane potential caused by input

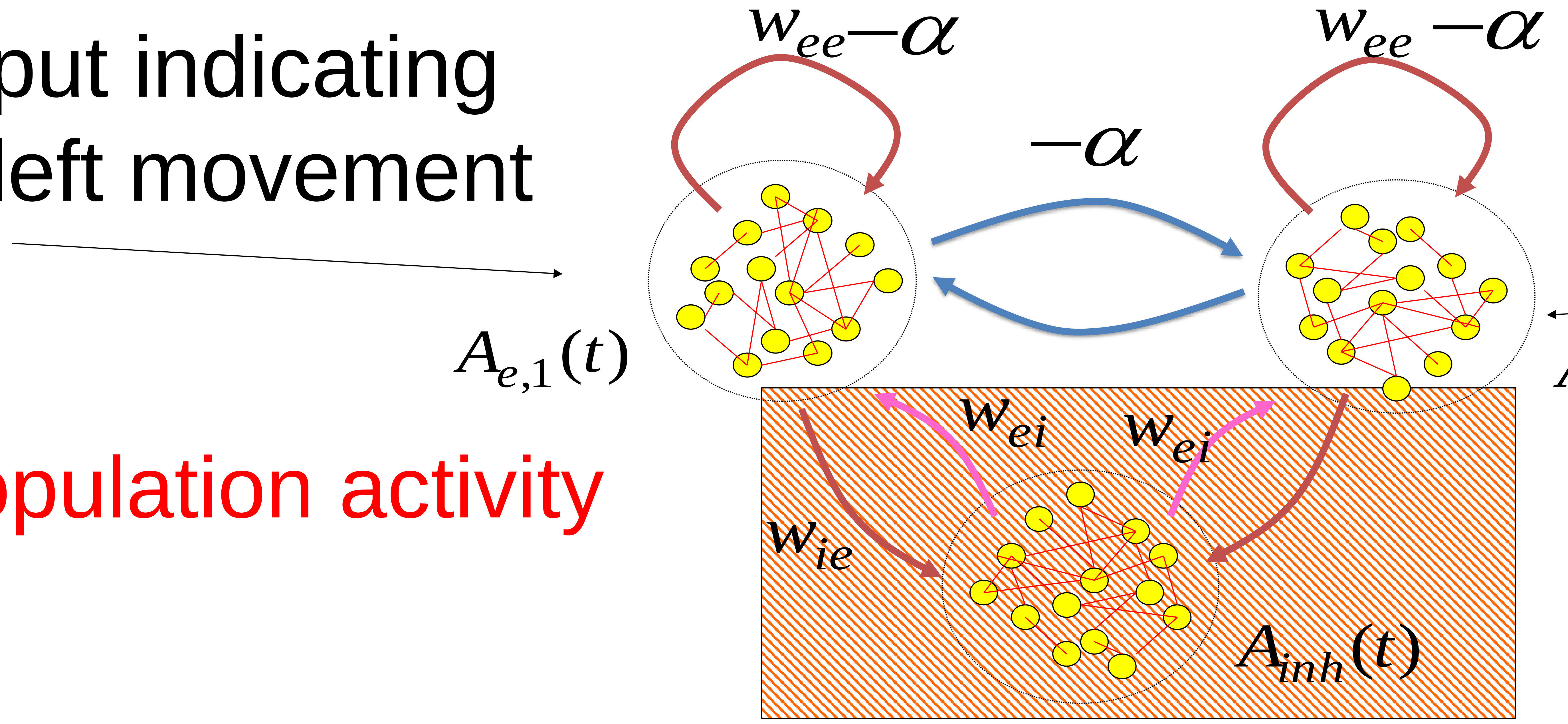
$$\tau \tfrac{d}{dt} h_1(t) = -h_1(t) + h_1^{ext}(t) + (w_{ee} - \alpha) F(h_1(t)) - \alpha F(h_2(t))$$

$$\tau \tfrac{d}{dt} h_2(t) = -h_2(t) + h_2^{ext}(t) + (w_{ee} - \alpha) F(h_2(t)) - \alpha F(h_1(t))$$

Input indicating left movement

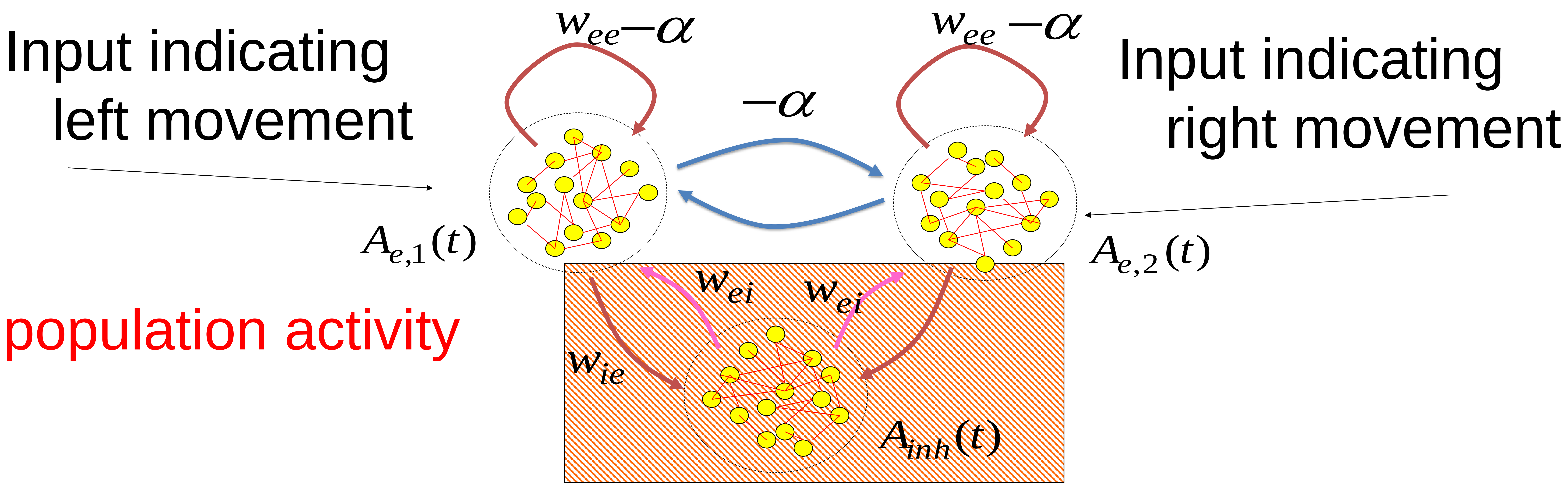
Input indicating right movement

population activity



# 3. Effective 2-dim. model

- two populations ‘compete’:
  if one shows high activity, it inhibits the other
- effective inhibitory interaction



# Quiz: Competitive dynamics

Which of the following statements are correct?

[ ] If two populations compete with each other, it is not possible that both are highly active.
[ ] If two populations compete with each other, it is possible that both are inactive.
[ ] If two populations compete with each other, one highly active population implies that the second one has low activity
[ ] Competition between populations can be implemented by shared inhibition

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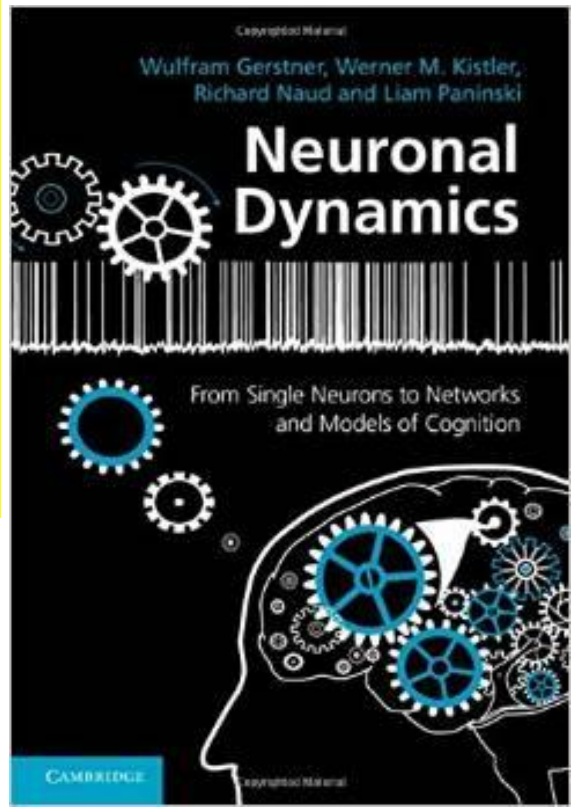


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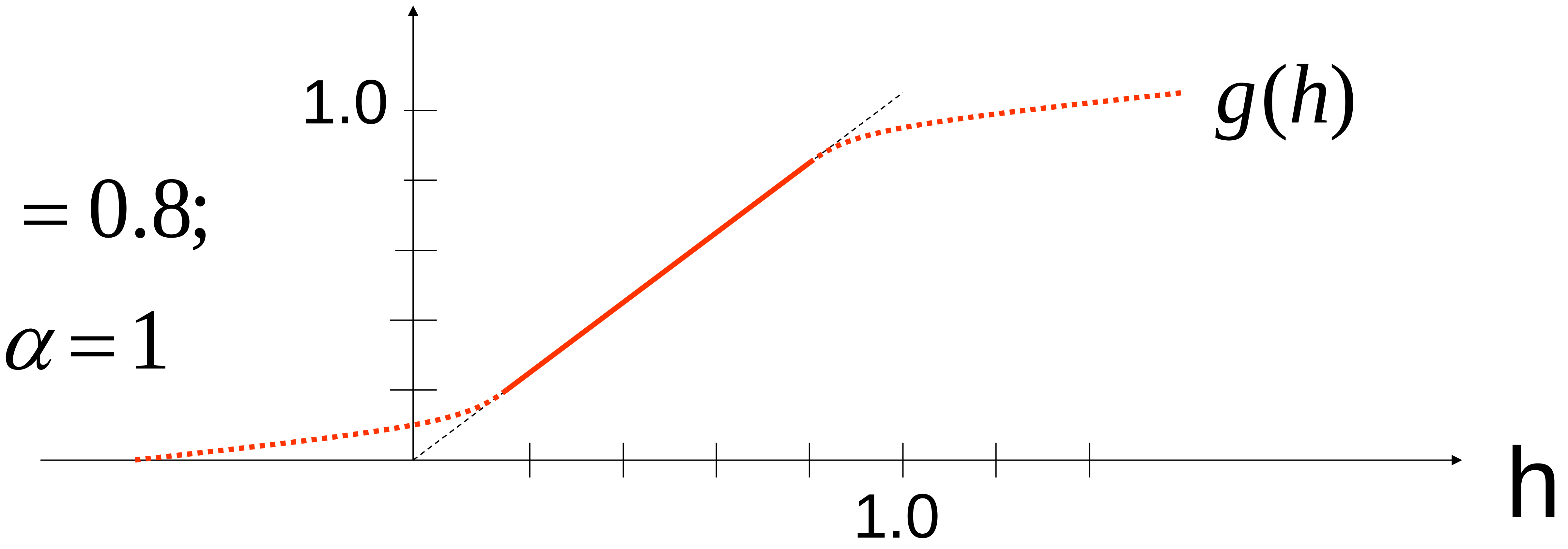
# 4. Theory of decision dynamics

$$\tau \frac{d}{dt} h_1(t) = -h_1(t) + h_1^{ext}(t) + (w_{ee} - \alpha) g(h_1(t)) - \alpha\, g(h_2(t))$$

$$h_1^{ext} = h_2^{ext} = 0.8;$$

$$w_{ee} = 1.5; \;\; \alpha = 1$$




$$g(h\;\;) = h \quad for \;\; 0.2 < h < 0.8$$

$$g(0) = 0.1$$

$$g(1) = 0.9$$

$\frac{d}{dt} h_1 = 0$

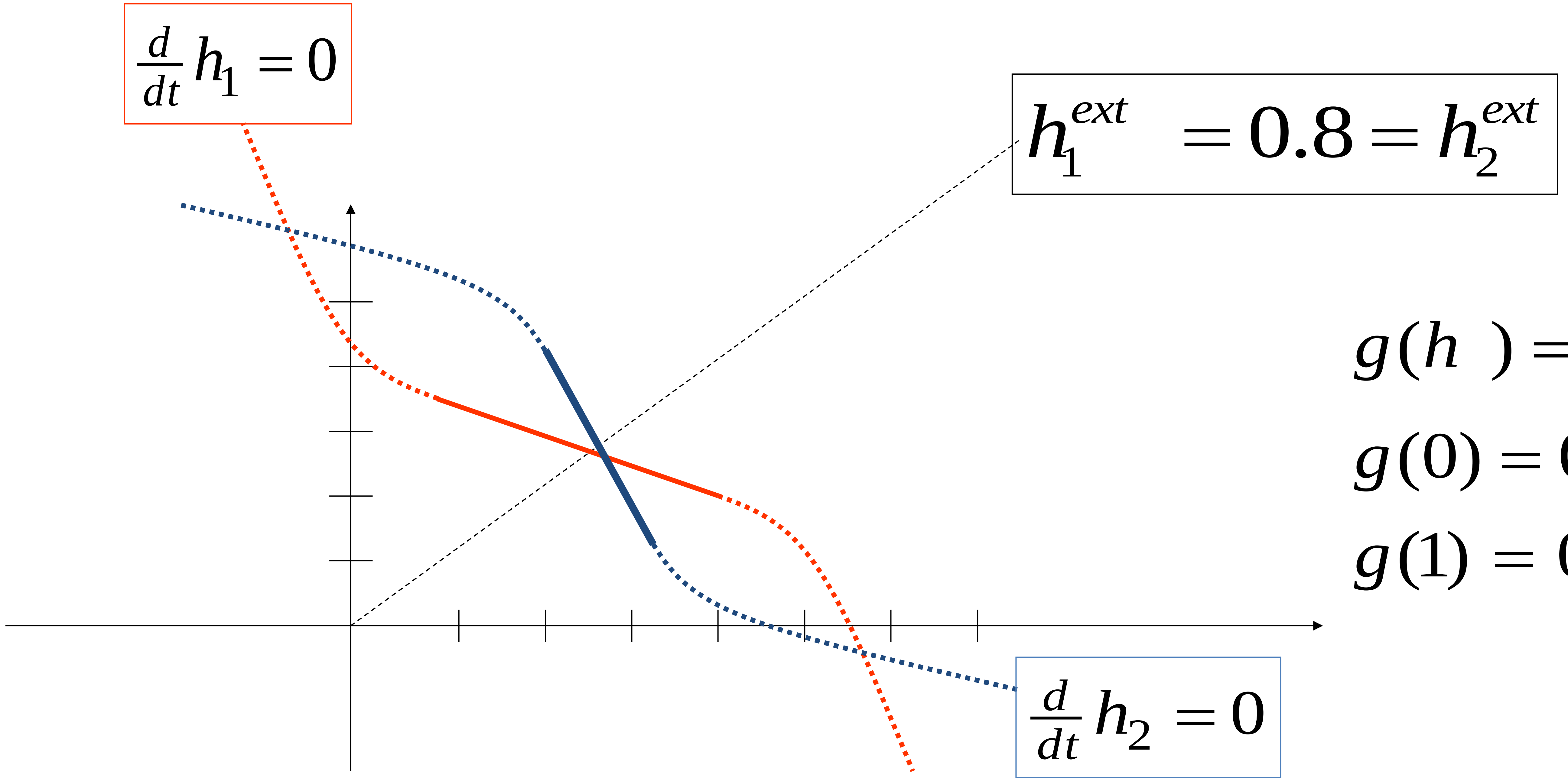
| $h_1$ | $g(h_2)$ | $h_2$ |
|---|---|---|
| 1.0 | | |
| 0.8 | | |
| 0.2 | | |
| 0.0 | | |

$\frac{d}{dt} h_2 = 0$

| $h_2$ | $g(h_1)$ | $h_1$ |
|---|---|---|
| 1.0 | | |
| 0.8 | | |
| 0.2 | | |
| 0.0 | | |

# 4. Theory of decision dynamics

## Phase plane, strong external input




$$g(h) = h \quad for \;\; 0.2 < h < 0.8$$

$$g(0) = 0.1$$

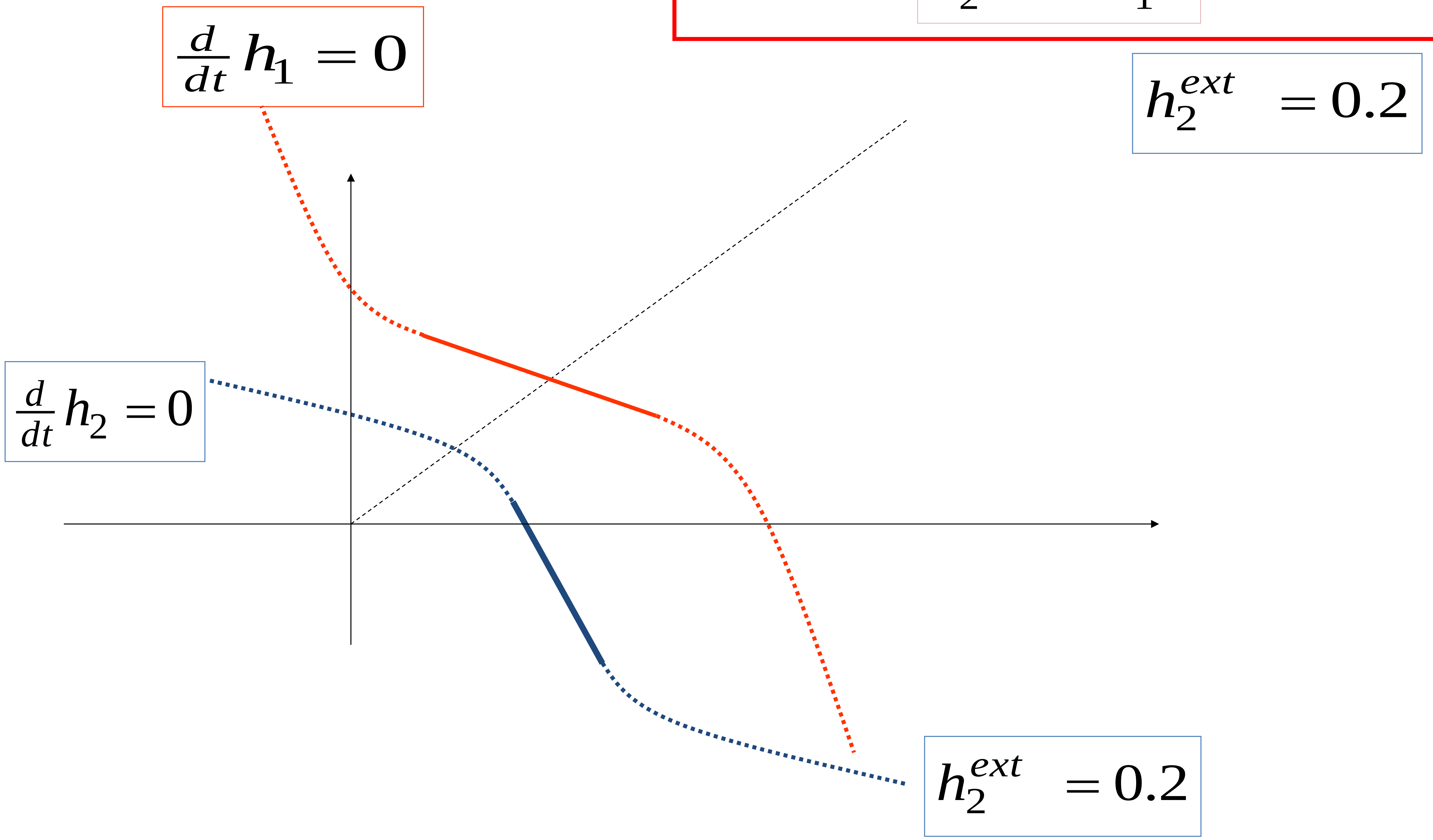
$$g(1) = 0.9$$

# 4. Theory of decision dynamics: biased input

Population activity

Phase plane – biased input:

$h_2^{ext} < h_1^{ext}$

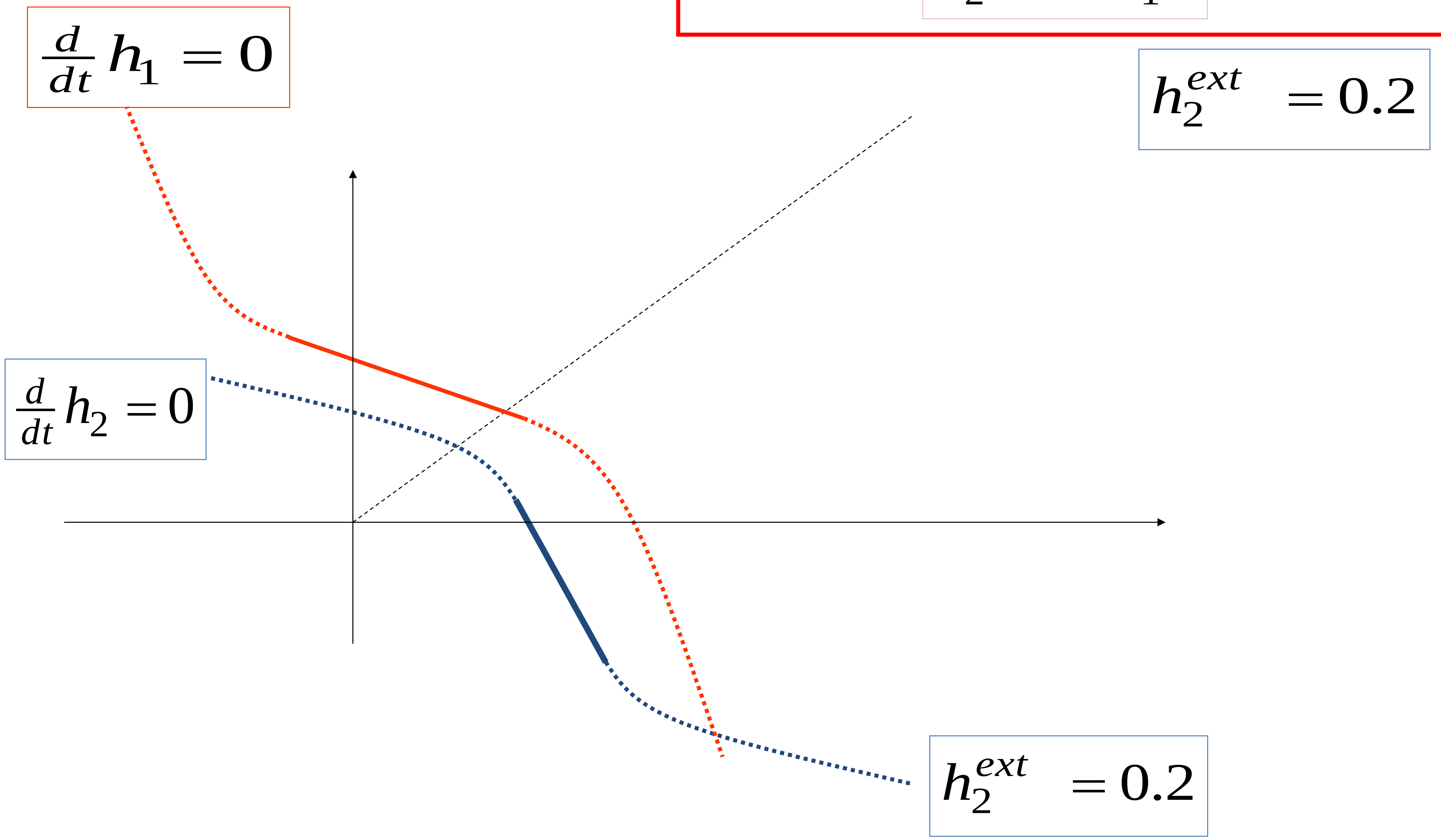


# 4. Theory of decision dynamics: biased input

Population activity

Phase plane – biased input:

$h_2^{ext} < h_1^{ext}$

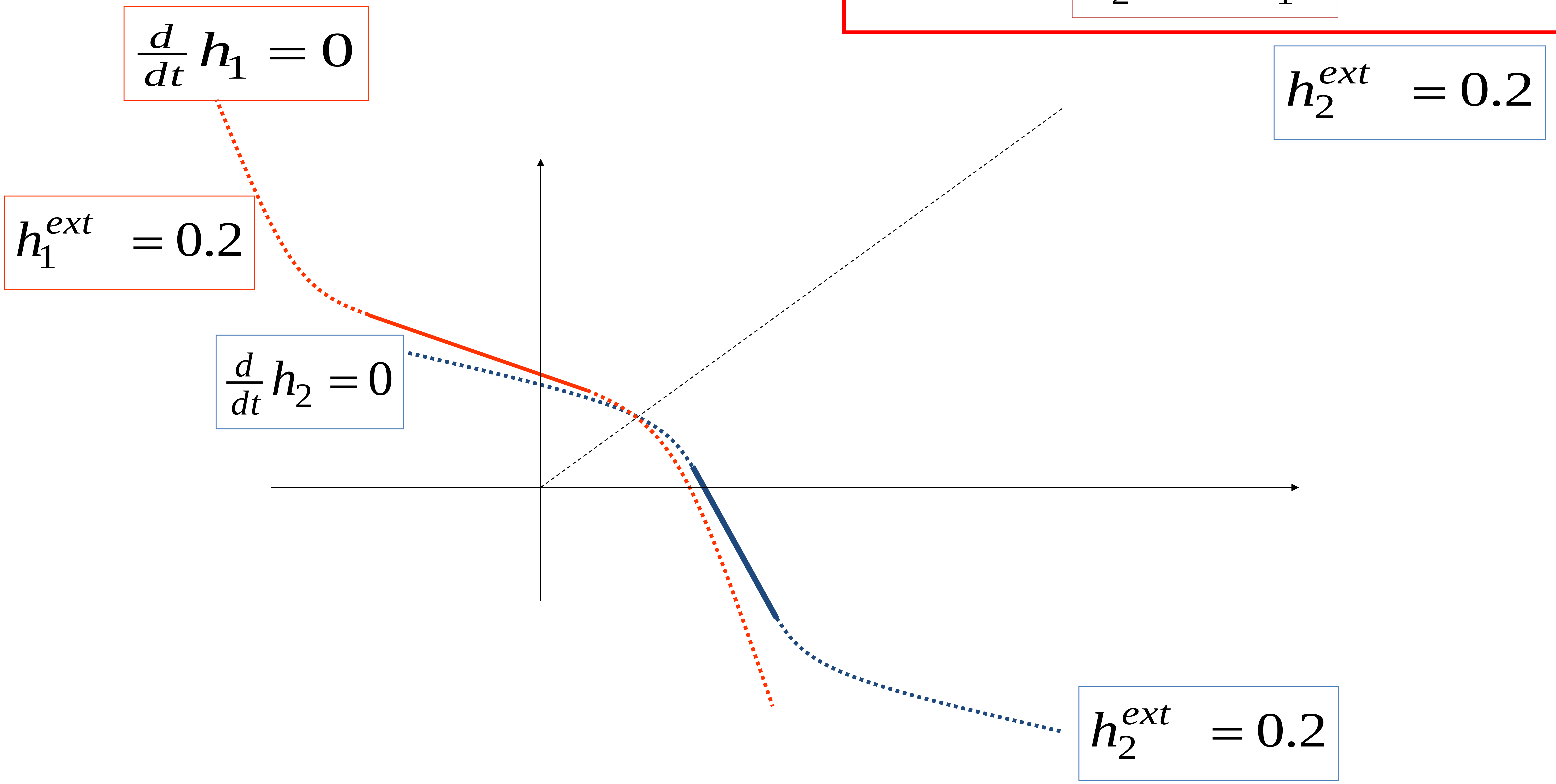


# 4. Theory of decision dynamics: biased input

Population activity

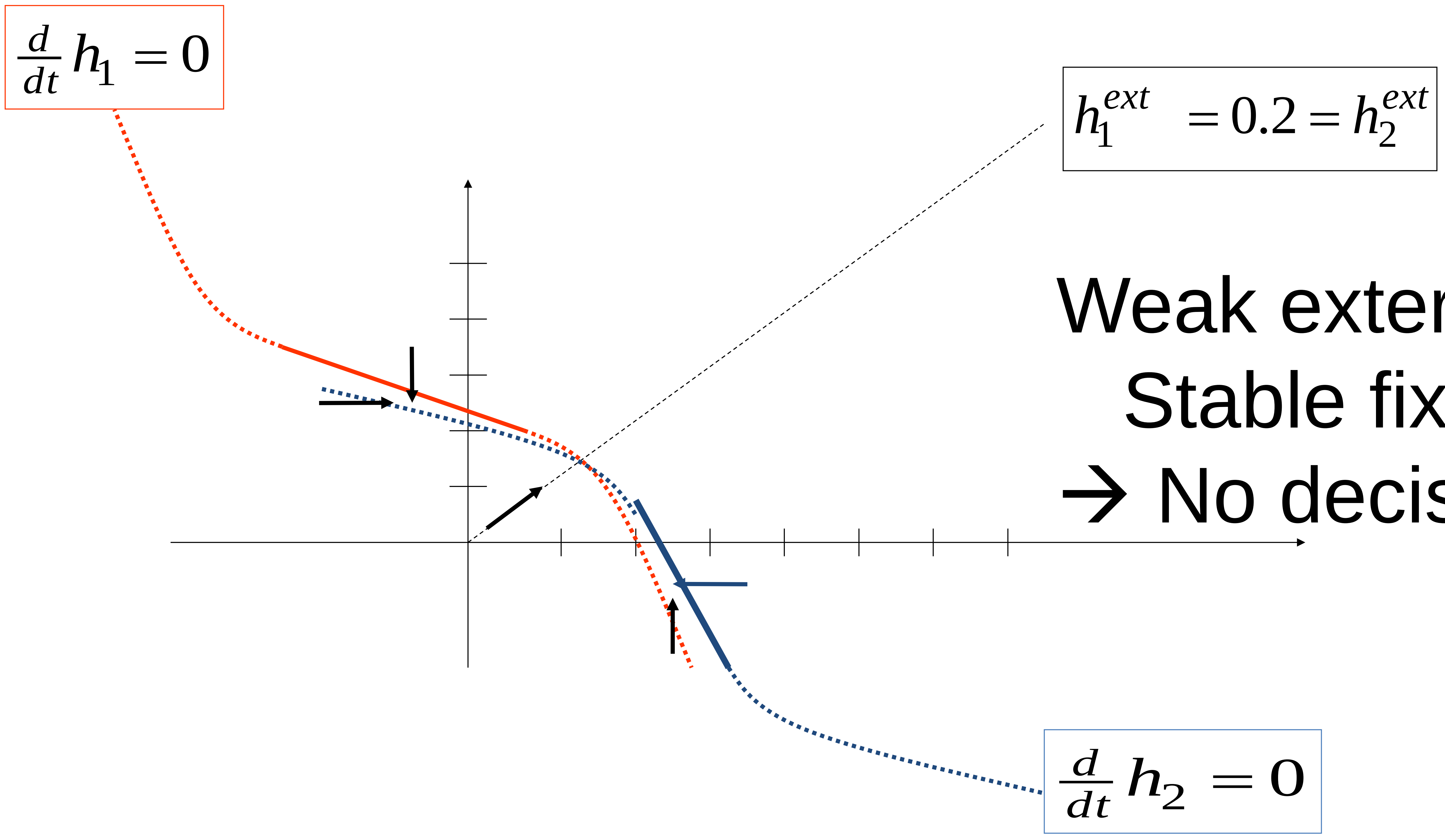
Phase plane – biased input:

$h_2^{ext} < h_1^{ext}$



# 4. Theory of decision dynamics: unbiased weak

## Phase plane – symmetric but small input

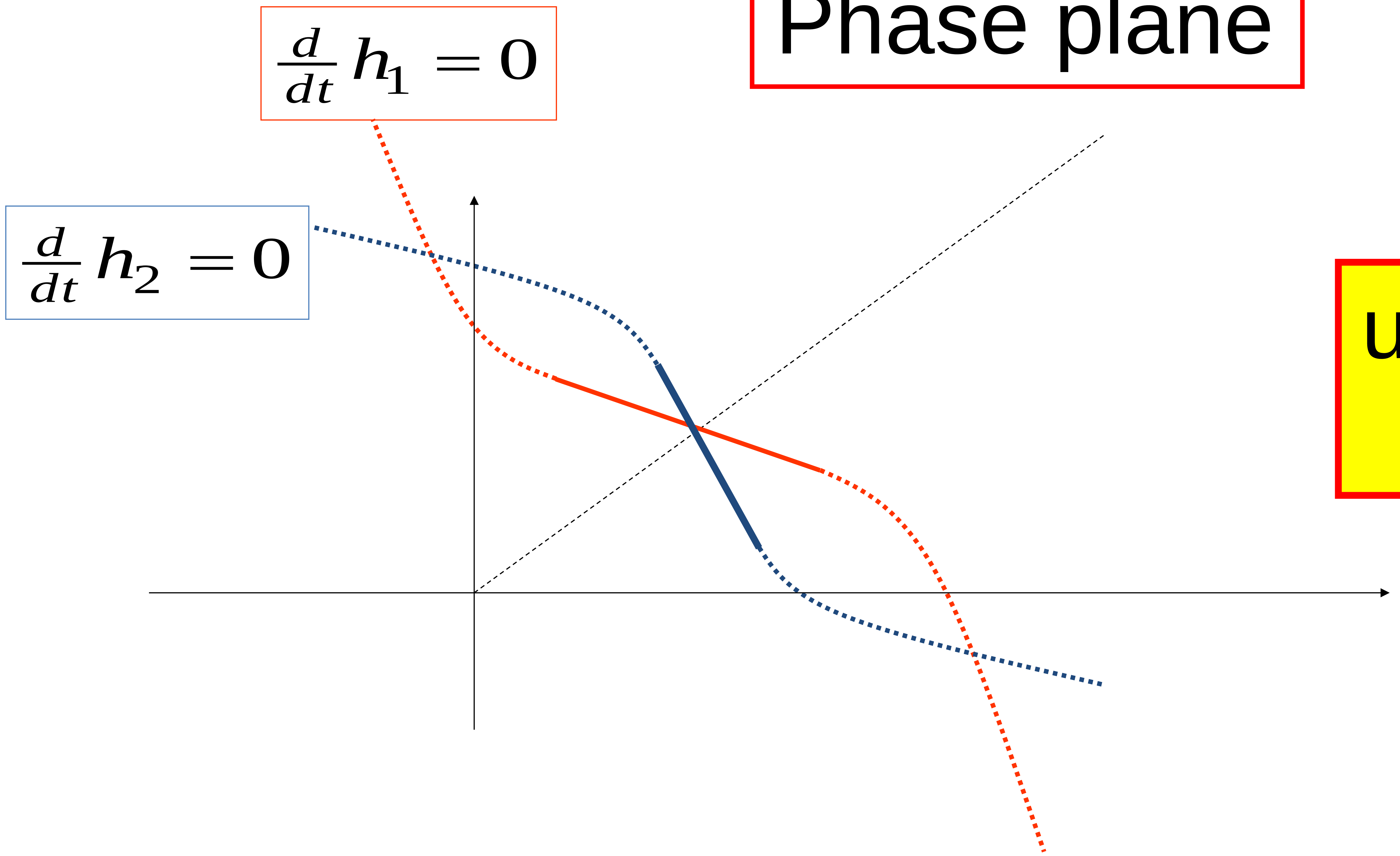



Weak external input:
Stable fixed point
→ No decision taken

# 4. decision dynamics: unbiased strong to biased

Symmetric, but strong input

Phase plane

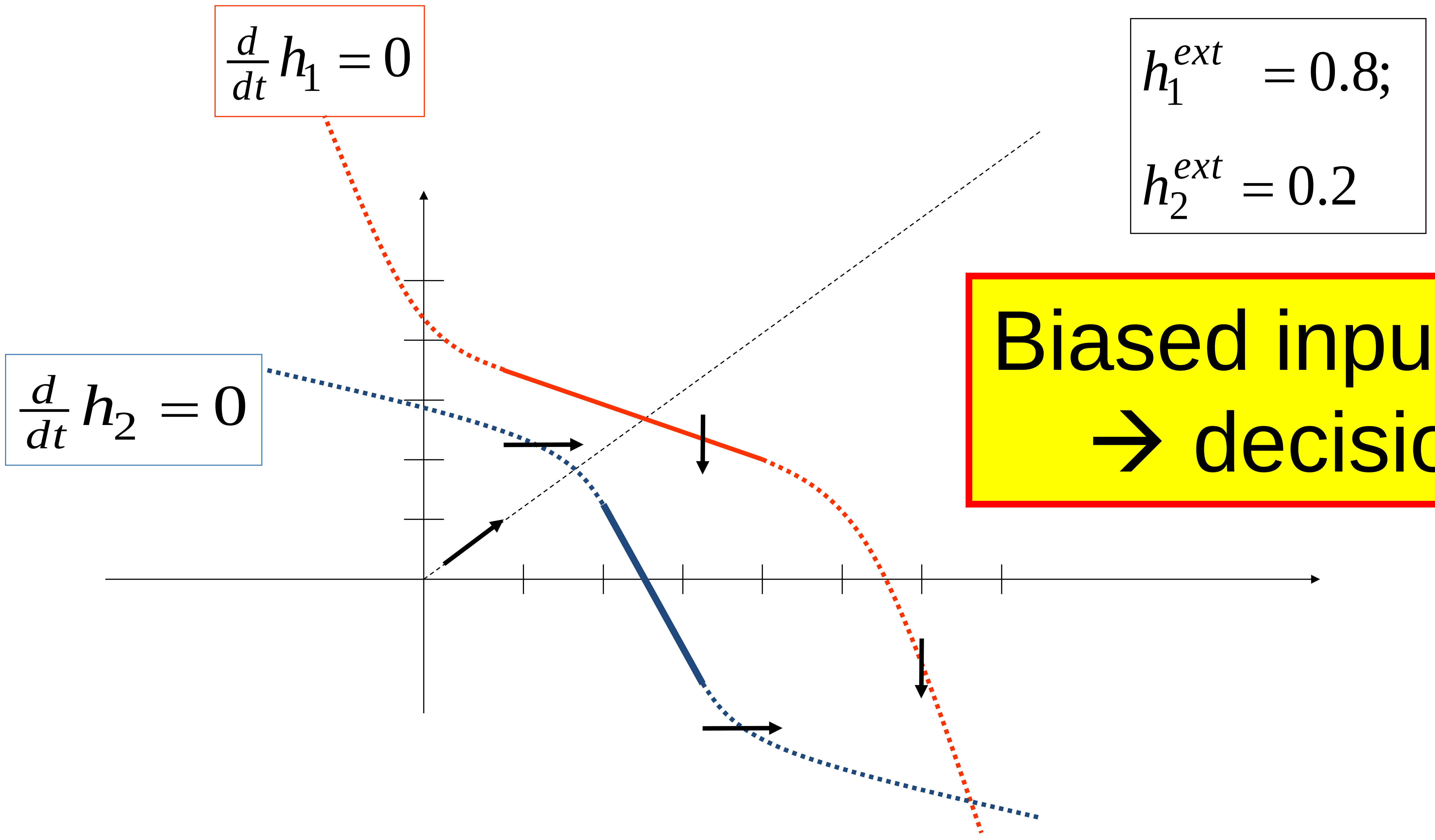



unbiased strong input
= 2 stable fixed points

# 4. Theory of decision dynamics: biased strong

Population activity

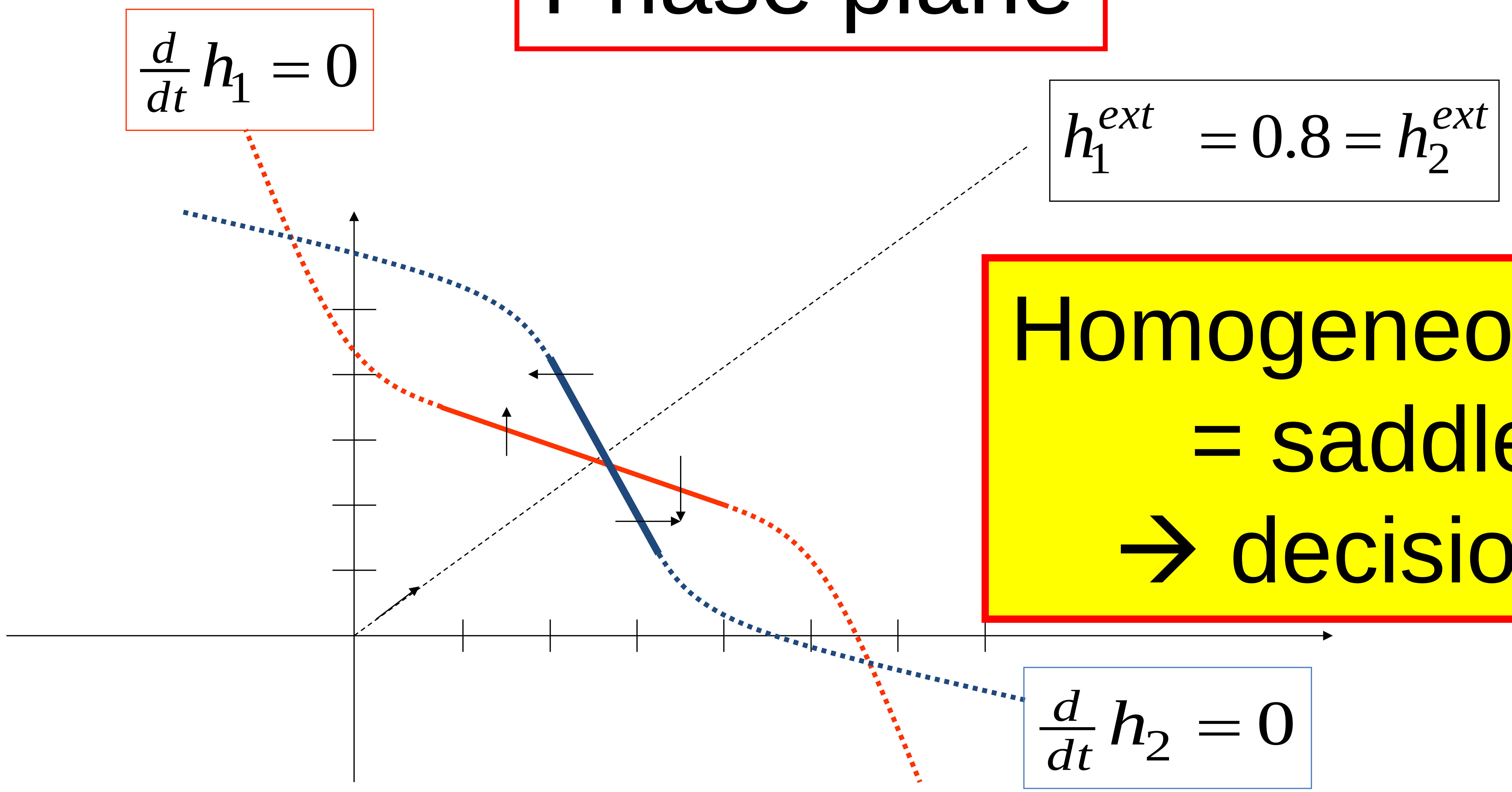
Phase plane




Biased input = stable fixed point
→ decision reflects bias

# 4. Theory of decision dynamics: unbiased strong

Phase plane




Homogeneous solution
= saddle point
→ decision must be taken

# Quiz: Competitive dynamics

Which of the following statements are correct?

[ ]  For symmetric weak input, our competitive model system has a single fixed point.
[ ]  For symmetric strong input, our competitive model system has a single fixed point.
[ ]  For biased strong input, our competitive model system has a single fixed point.
[ ]  For symmetric strong input, our competitive model system must take a decision
[ ]  For biased strong input, our competitive model system must take a decision
[ ] Taking a decision corresponds to a movement toward an asymmetric stable fixed point of the dynamics

# Computational Neuroscience: Neuronal Dynamics of Cognition

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

## Decision models:

## Competitive dynamics

Wulfram Gerstner

EPFL, Lausanne, Switzerland

*Reading for week 9*:
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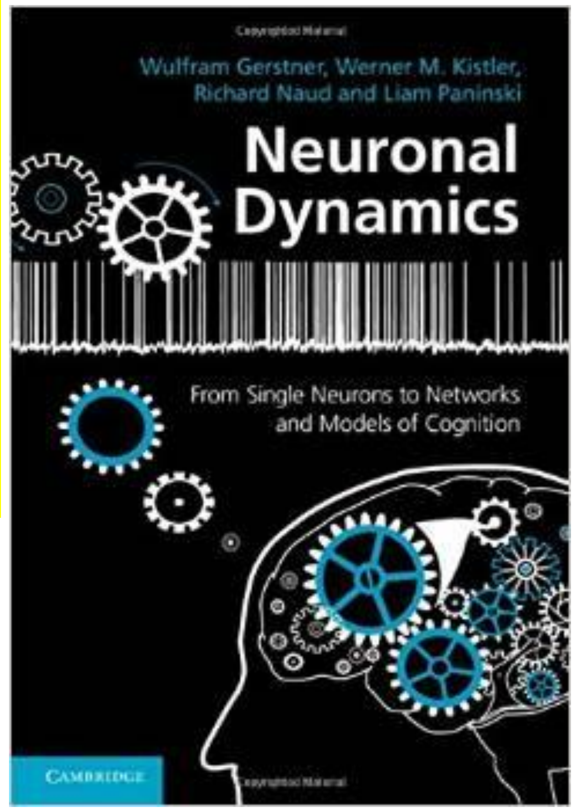
Ch. 16 (except 16.4.2)

Cambridge Univ. Press

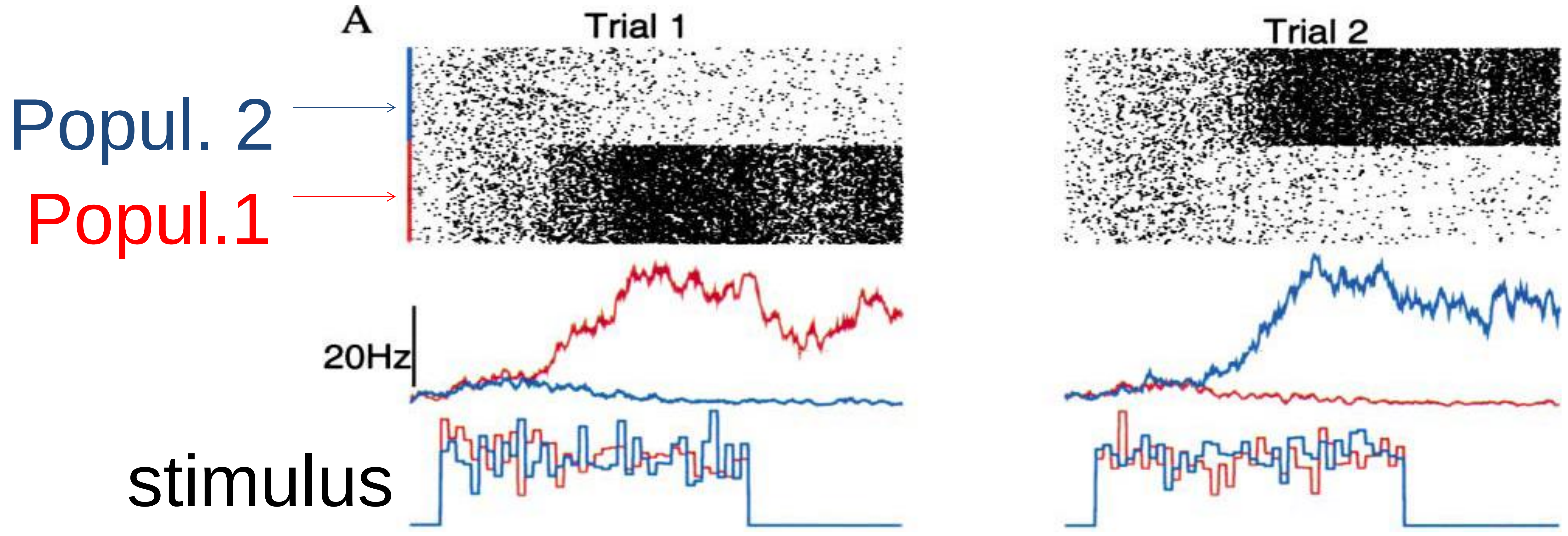


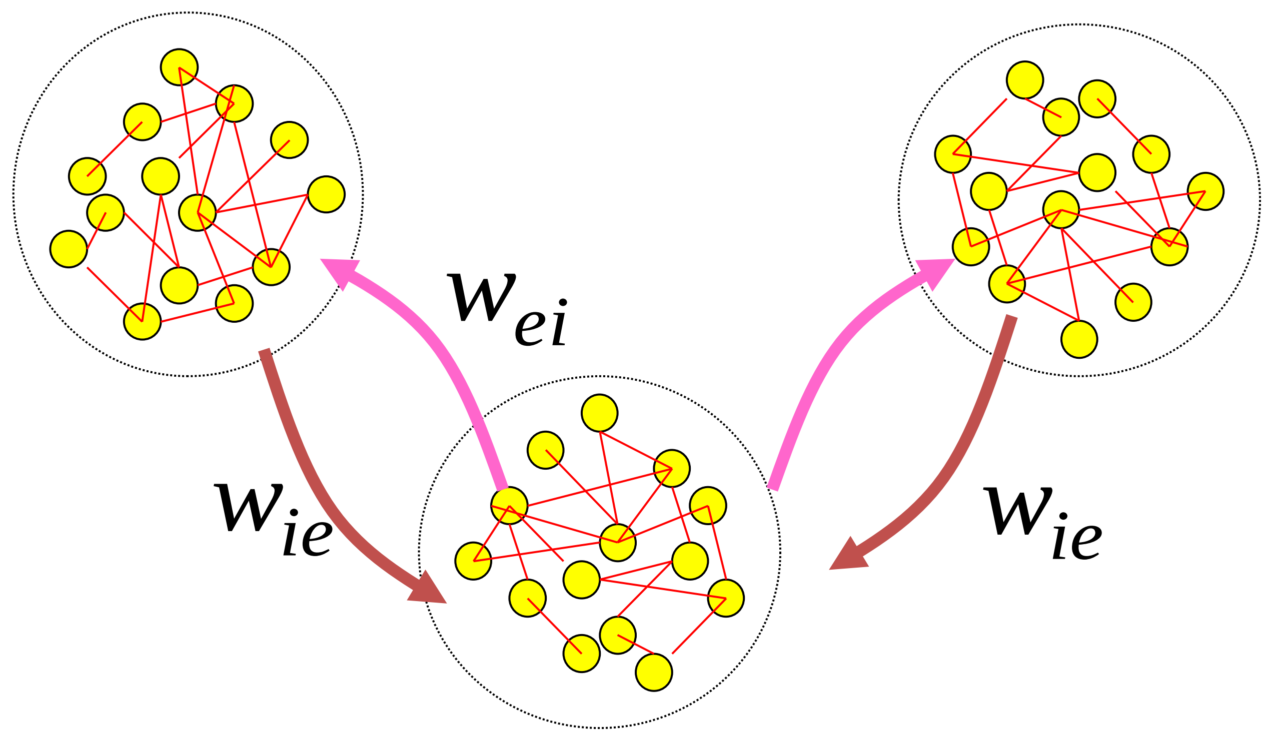

1. **Introduction**
   - decision making
2. **Perceptual decision making**
   - V5/MT
   - Decision dynamics: Area LIP
3. **Theory of decision dynamics**
   - competition via shared inhibition
   - effective 2-dim model
4. **Solutions**
   - symmetric case
   - biased case
5. **Simulations and Experiments**
   - simulations and theory
   - simulations and experiments
6. **Decisions, actions, volition**
   - the problem of free will

# 5. Decisions in populations of neurons: simulation

Simulation of 3 populations of spiking neurons, unbiased strong input

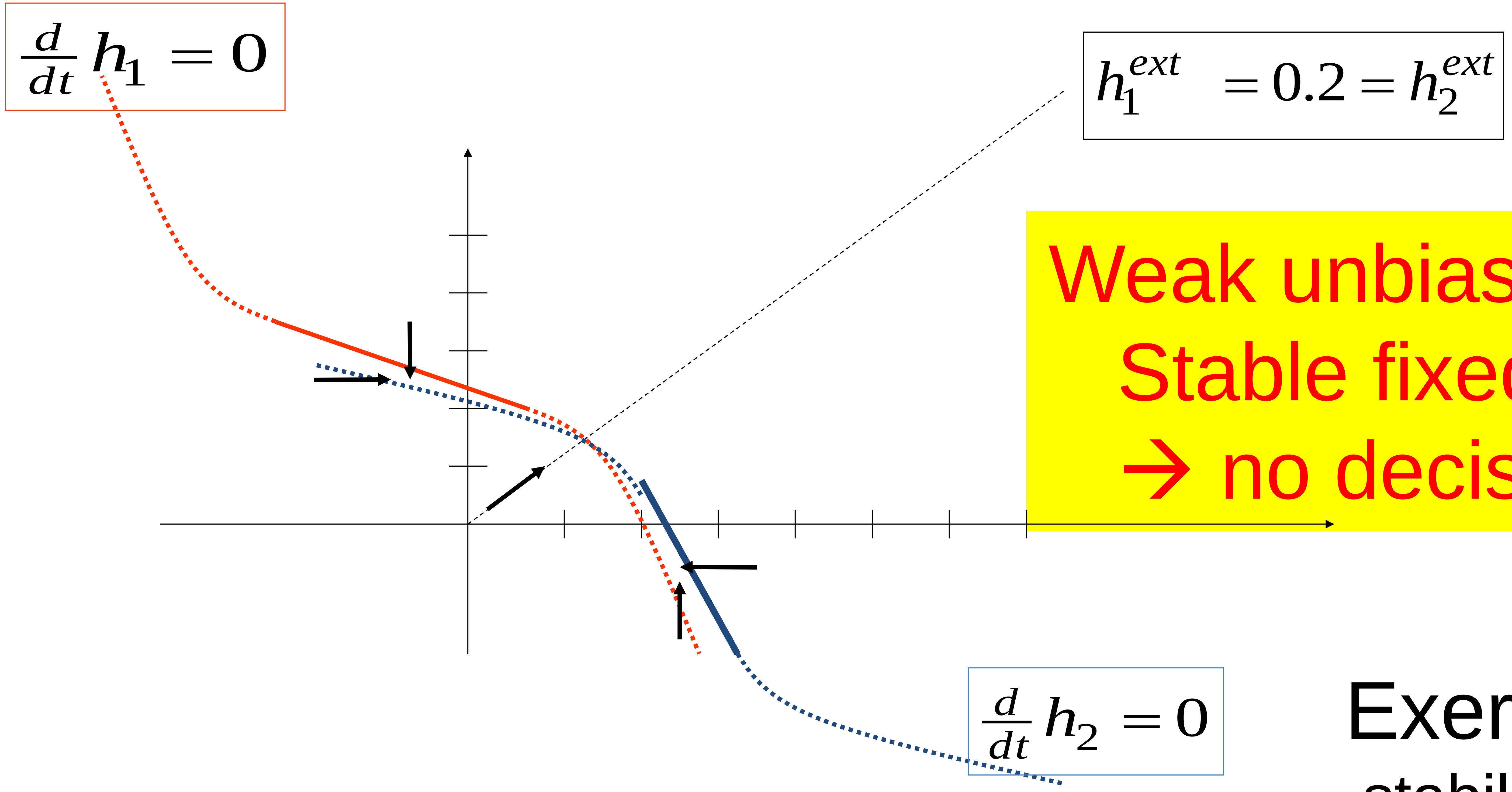
*X.J. Wang, 2002*
*NEURON*



# 5. Comparison: Simulation and Theory

1) Before stimulus is given: symmetric but small input



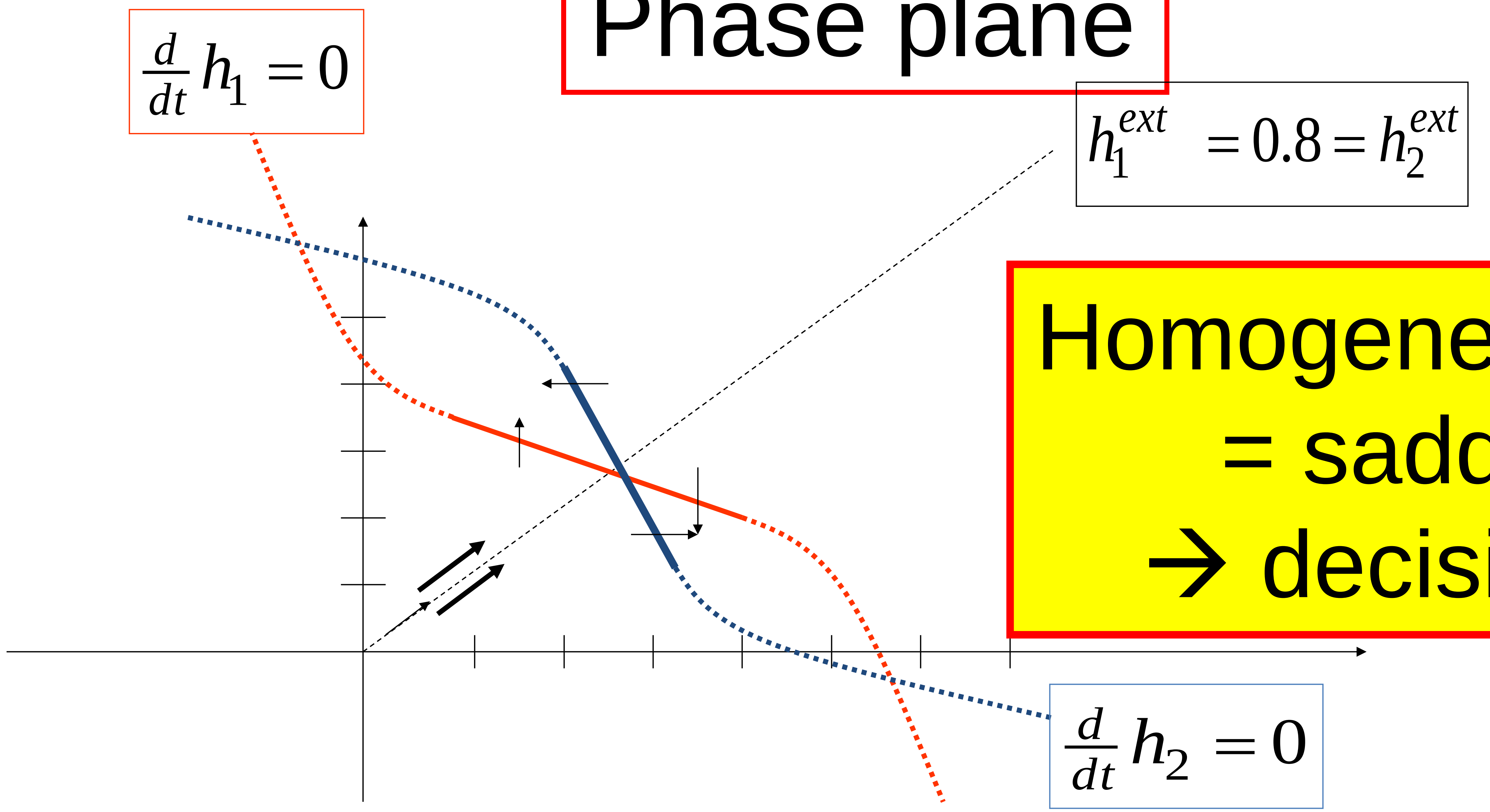

Weak unbiased input:
Stable fixed point
→ no decision

Exercise 2 at home:
stability of symmetric solution

# 5. Comparison: Simulation and Theory

2) When stimulus is given: symmetric but strong input

Phase plane




Homogeneous solution
= saddle point
→ decision must be taken

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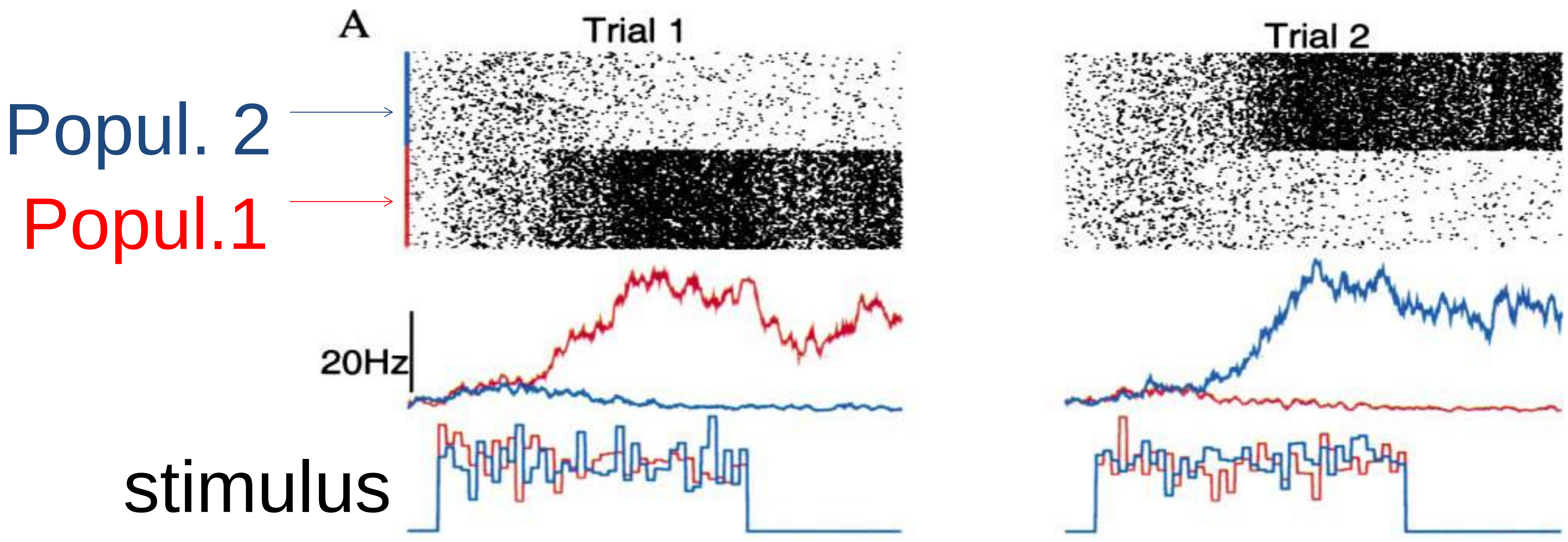
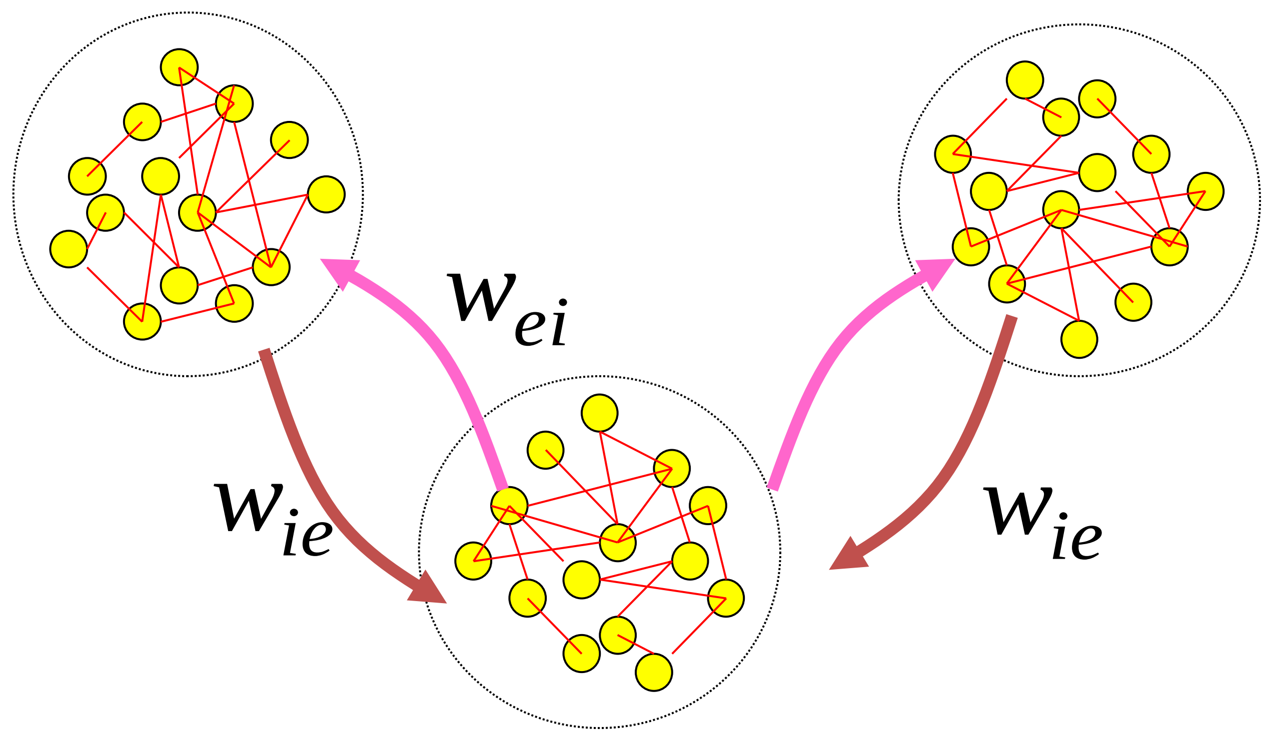
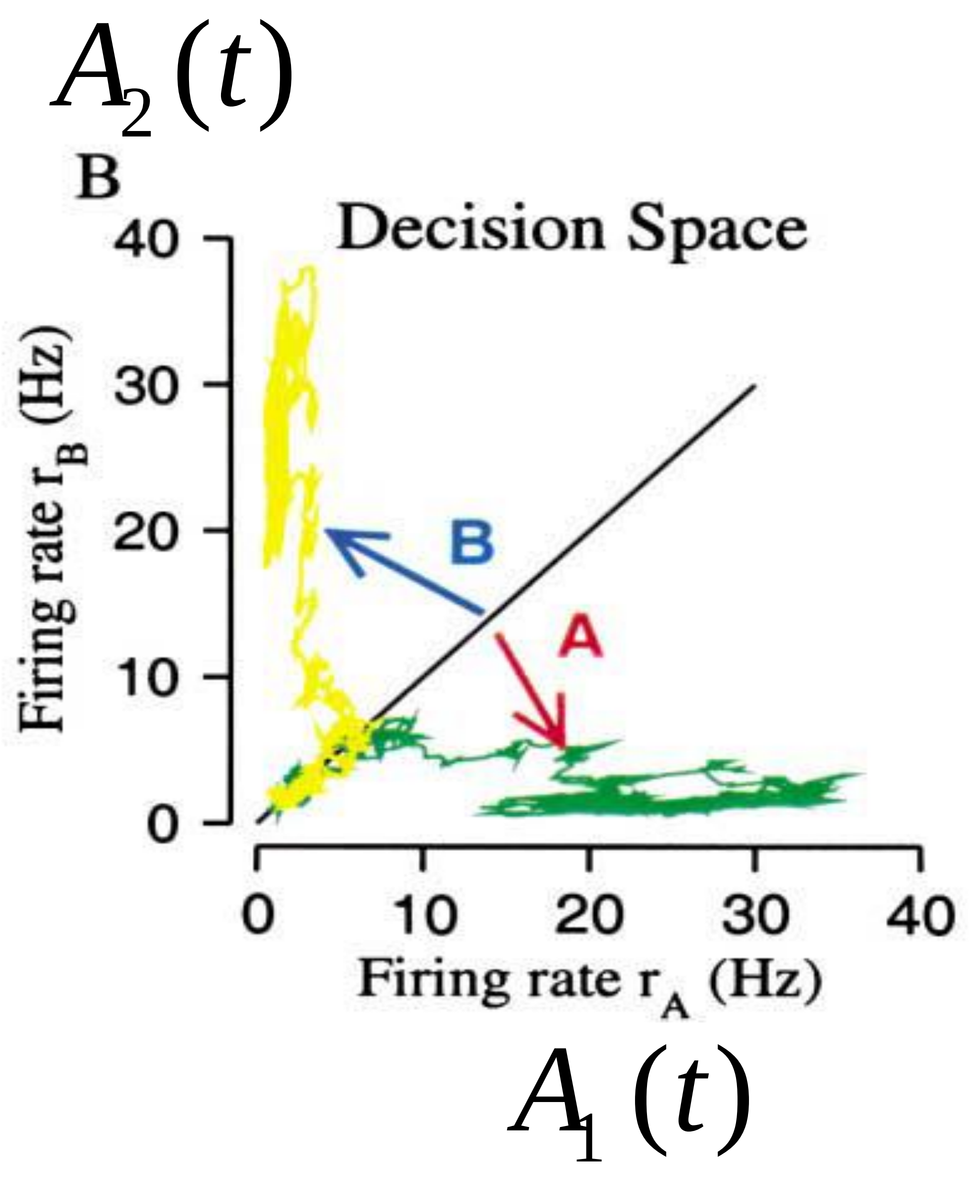


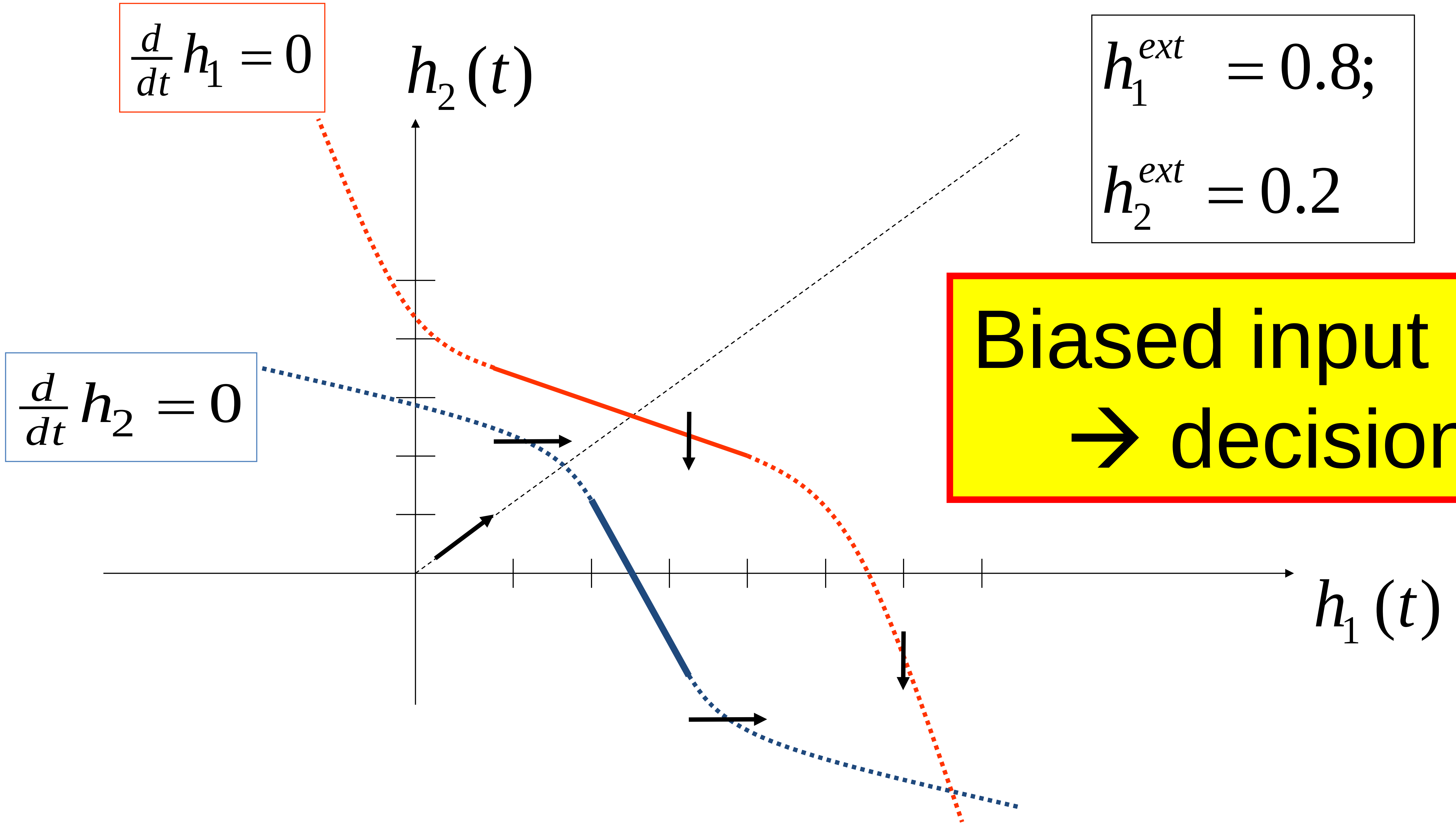



# 5. Comparison with experiment: biased strong input

Prediction by theory - for input potential $h_1(t)$

- population activity $A(t) = F(h(t))$

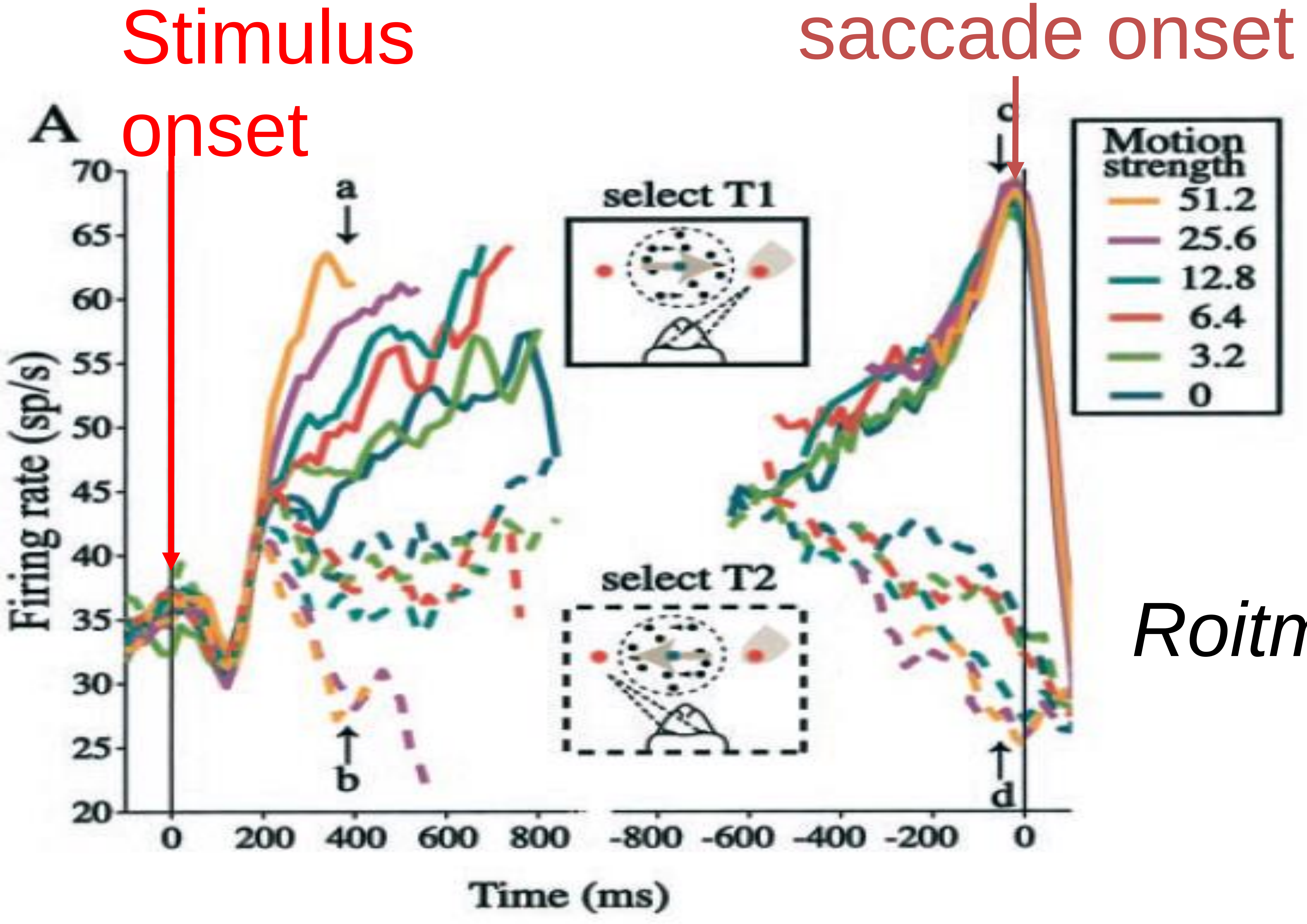



$h_1^{ext} = 0.8;$

$h_2^{ext} = 0.2$

Biased input = stable fixed point
→ decision reflects bias

# 5. Decisions in populations of neurons: LIP data




*Roitman and Shadlen 2002*

*Figure 7.* Time course of LIP activity in the RT-direction-discrimination task. *A*, Average response from 54 LIP neurons. Responses are grouped by motion strength and choice as indicated by *color* and *line type*. The responses are aligned to two events in the trial. On the *left*, responses are aligned to the onset of stimulus motion. Response averages in this portion of the graph are drawn to the median RT for each motion strength and exclude any activity within 100 msec of eye movement initiation. On the *right*, responses are aligned to initiation of the eye movement response. Response averages in this portion of the graph show the buildup and decline in activity at the end of the decision process. They exclude any activity within 200 msec of motion onset. The average firing rate was smoothed using a 60 msec running mean. *Arrows* indicate the epochs used to compare spike rate as a function

# 5. Decisions in populations of neurons: LIP data

simulation of competing populations shares properties with data:

- faster increase for strong bias
- suppression for opposite saccade

BUT: there is no claim that decision is taken in LIP

LIP is somewhere in the processing stream from input to saccades

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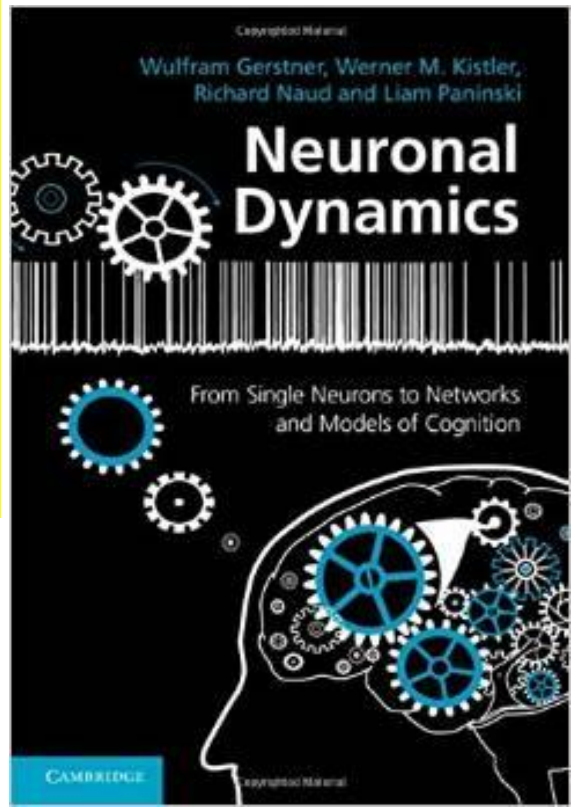


Cambridge Univ. Press

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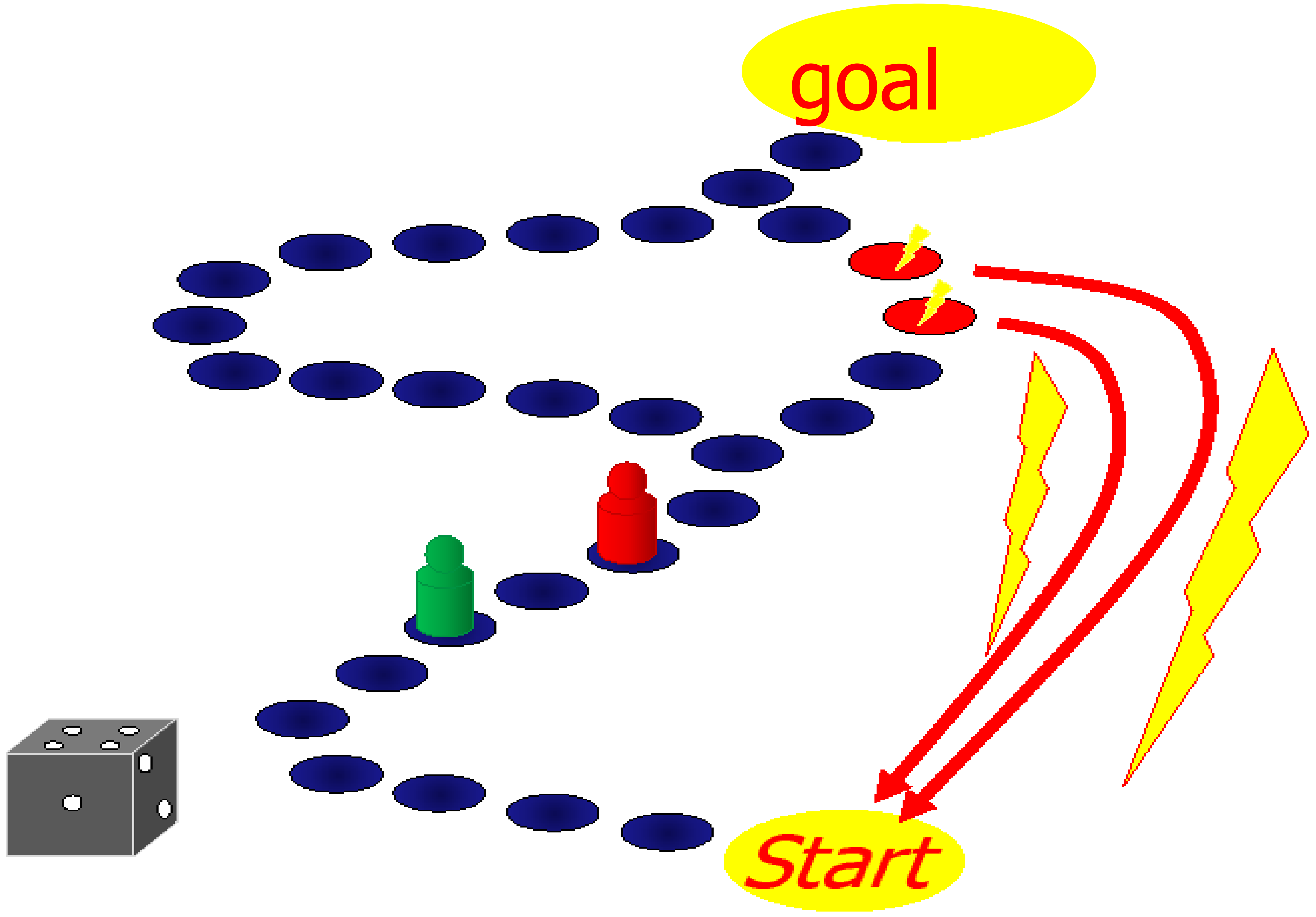
- the problem of free will

# 6. Decision: risky vs. safe

How would you decide?



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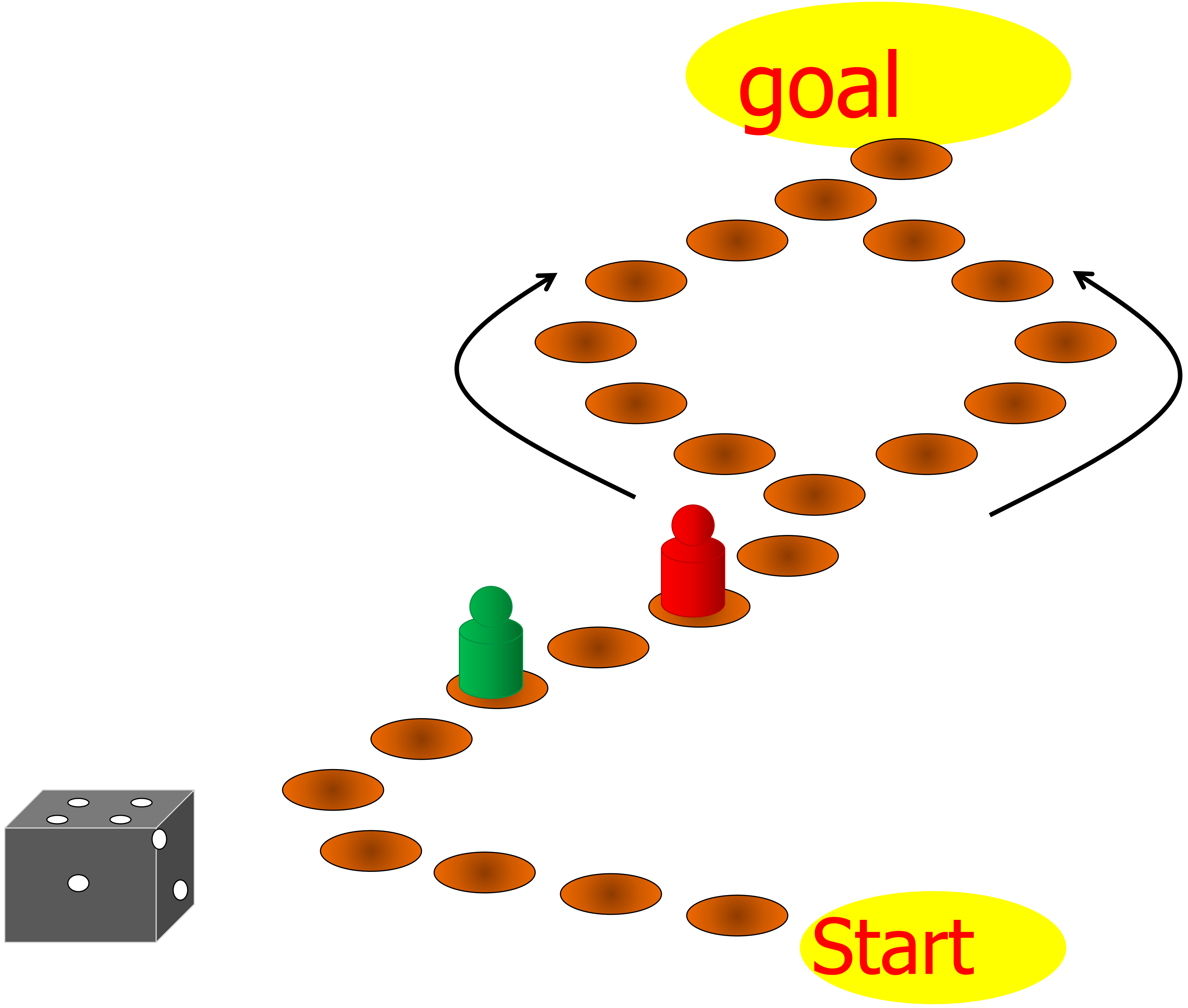
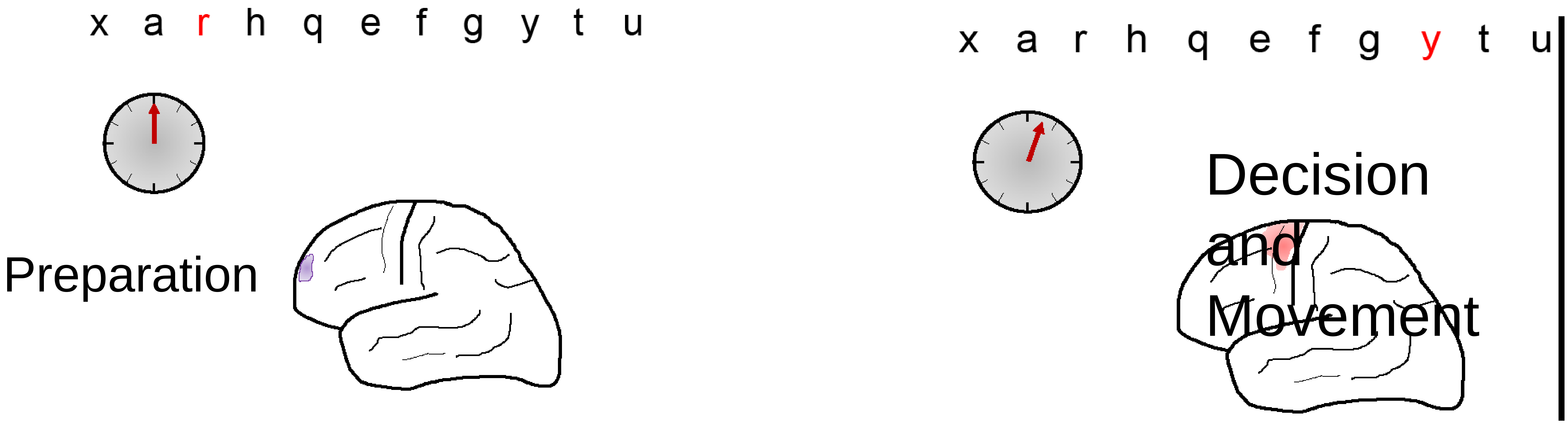
How would you decide?



# 6. fMRI variant of Libet experiment: volition and free will




-Subject decides spontaneously
to move left or right hand
- report when they made their decision

*Libet, Behav. Brain Sci., 1985*
*Soon et al., Nat. Neurosci., 2008*

# What decides? Who decides?

*'Your brain decides what you want or what you prefer … '*

' … but your brain – this is you!!!'

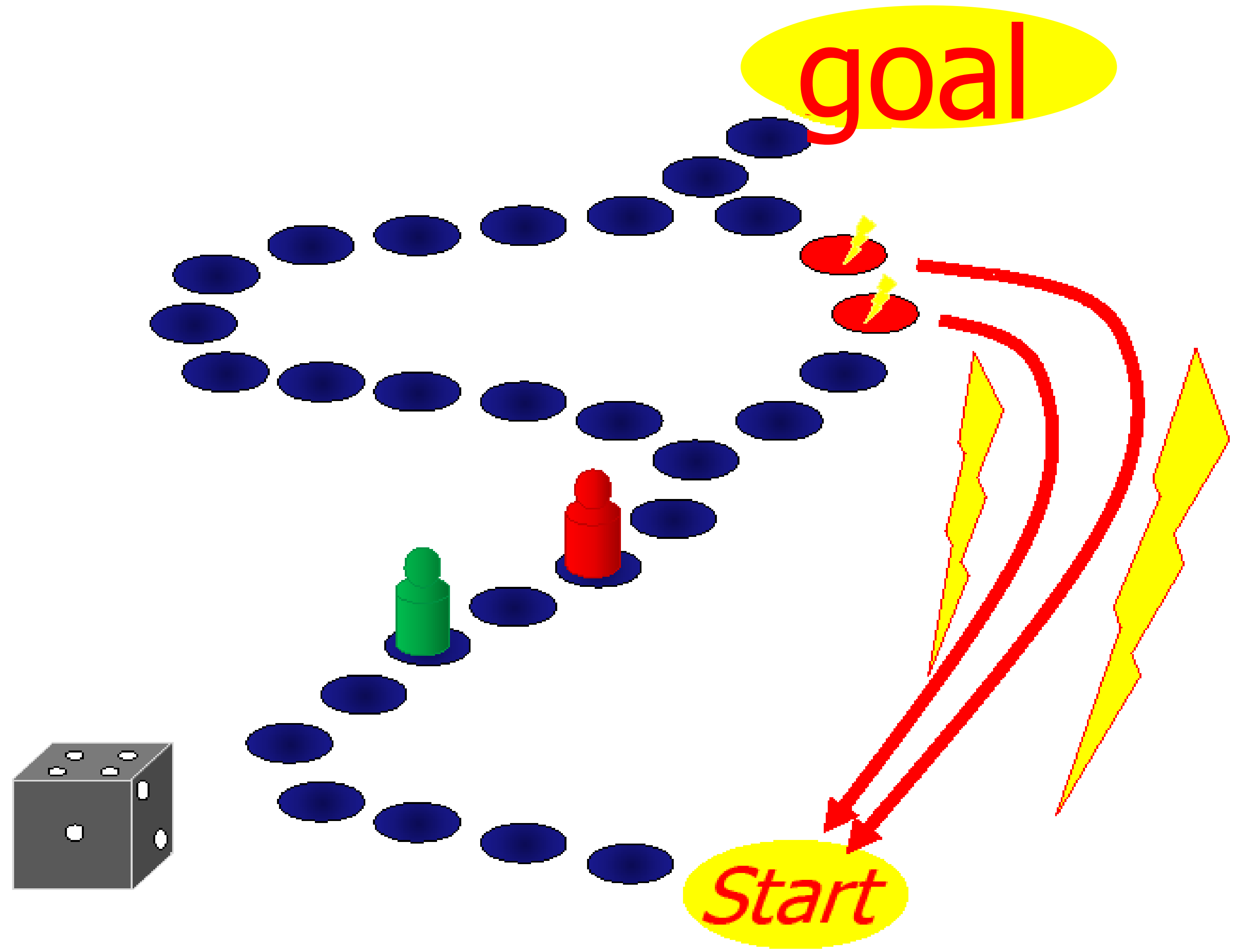
-Your experiences are memorized in your brain
-Your values are memorized in your brain
-Your decisions are reflected in brain activities

*'We don't do what we want, but we want what we do' (W. Prinz)*


The problem of Free Will (see e.g. Wikipedia article)

# 6. Decision: risky vs. safe

- decisions are taken in the brain
- competing populations is a transparent model
- relevant decisions involve personal values and experiences



# 6. Selected References: Decision Making

Suggested Reading:
- *Salzman et al. Nature 1990*
- *Roitman and Shadlen, J. Neurosci. 2002*
- *Abbott, Fusi, Miller: Theoretical Approaches to Neurosci.*
- *X.-J. Wang, Neuron 2002*
- *Libet, Behav. Brain Sci., 1985*
- *Soon et al., Nat. Neurosci., 2008*
- *free will, Wikipedia*

Chapter 16, *Neuronal Dynamics*, Gerstner et al. Cambridge 2014